VISTA – A CONSTELLATION FOR REAL TIME REGIONAL IMAGING

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Abstract. The role of satellites in medium and high-resolution reconnaissance of the Earth has been well demonstrated in recent years through missions such as Landsat, SPOT, IKONOS, ImageSat and Quickbird. The market for such data products is well served and likely to become more competitive with further very-high-resolution missions. Whereas commercial markets have concentrated on enhancing resolution, the small satellite sector has concentrated on reducing the cost of data products, and the development of systems providing niche services. One such area that can be well served by smaller satellites is the need for higher temporal resolution, as this typically requires a large number of satellites to operate as a constellation.

Surrey is currently engaged in building its first constellation providing daily global coverage at moderate resolution in three spectral bands. Targeted at providing timely quick-look data products for disaster mitigation and monitoring, the constellation comprises 5 satellites in a single orbital plane. Each satellite has a wide swath so that successive satellites progressively cover the entire globe in a single day. The Vista constellation takes this concept a step further, and is proposed for applications requiring near-continuous surveillance of regional activity. By introducing a multiple plane constellation of small Earth Observation satellites, it is possible to monitor the entire globe continuously. The paper describes the system trades and outlines the scope of the performance that could be obtained from such a system. A cost model illustrates that the balance between launch and space segment costs must be reached by considering suitable replacement strategies, and that the system is highly sensitive to requirement creep. Finally, it is shown that the use of cost effective, small satellites leads to solutions previously thought to be out of reach of government customers.

Introduction

Whilst large imaging platforms such as the Spot and LandSat series provide an excellent source of imaging data that is widely used around the globe, such large costly spacecraft are not able to provide a cost-effective solution to the problem of temporal resolution.

The low cost of small satellites, however, allows the cost-effective use of multiple satellites to provide a more rapid imaging revisit.

This paper illustrates some general examples of the scale and frequency of imaging coverage that may be achieved with constellations of small low cost satellites.

Current SSTL Missions

SSTL has manufactured and launched several Earth Observation missions[1] with a multitude of imagers. They are currently constructing another five Earth imaging spacecraft for a variety of international and domestic customers. These spacecraft are providing capabilities ranging from large area 32m GSD multi-spectral imaging down to approximately 2.5m GSD Pan-chromatic targeted observation.

SSTL's first constellation mission, the Disaster Monitoring Constellation (DMC)[2 3] is a constellation of enhanced micro-satellites that will provide the capability of daily global imaging. SSTL is currently manufacturing the first three satellites of the DMC.

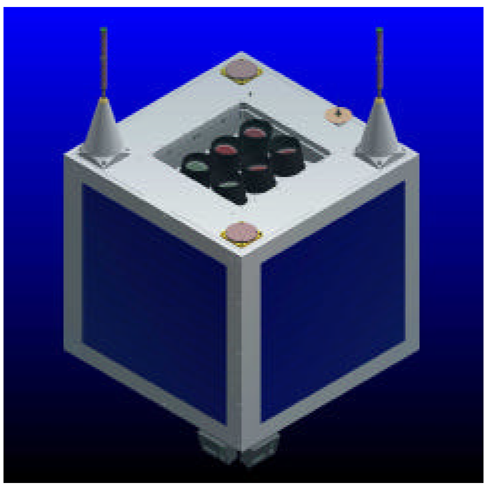

Figure 1 DMC Satellite

The constellation is to be launched in a staged approach. The first launch due to take place in late 2002 will launch a single DMC spacecraft.

This will be followed approximately 8 months later by the launch of the second and third DMC satellites.

When the 3rd DMC launch delivers the final two of the five core DMC spacecraft to the same orbit the first DMC constellation will be complete.

The primary DMC imager provides a swath of approximately 600km (actually 640km at an altitude of 686km) with a Nadir GSD of approximately 32m.

The later of the DMC satellites also incorporate a 4m imager. The agile platform can off-point, for example, up to 30° and hence can typically provide imaging opportunities for a swath width in the region of 600km.

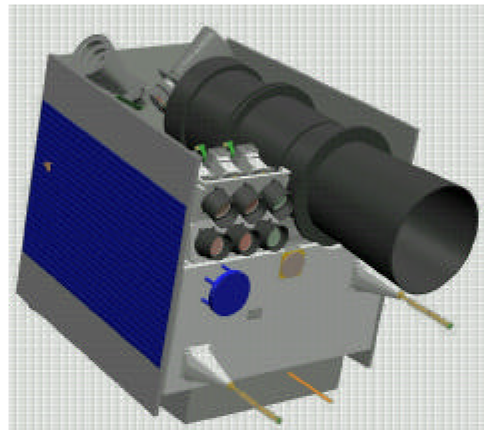

Figure 2 DMC+4 Satellite

This agile platform off-pointing capability is typical of other current SSTL spacecraft designs[4], and also other SSTL designs for the near future with additional propulsion capability.

In this paper an approximate 600km swath coverage is presented as a typical capability when considering the coverage of different constellation orbit configurations.

Constellation Scenarios and Coverage Possibilities

In this section several scenarios are presented that illustrate coverage examples that can be achieved with small, medium or large constellations of small low-cost satellites.

Global Coverage on a Daily Basis

The global daily coverage provided by the DMC, described earlier, is achieved by using multiple satellites in a single sun-synchronous orbit.

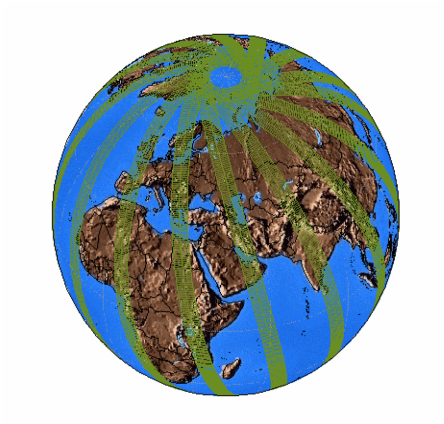

Figure 3 Daily Imaging Coverage of a Single DMC Satellite

It is the multiple satellites in the same orbit that provide the extensive ground coverage. The daily coverage of a single DMC satellite is shown in Figure 3 and Figure 4 (note sunlit sections of the orbits only are shown).

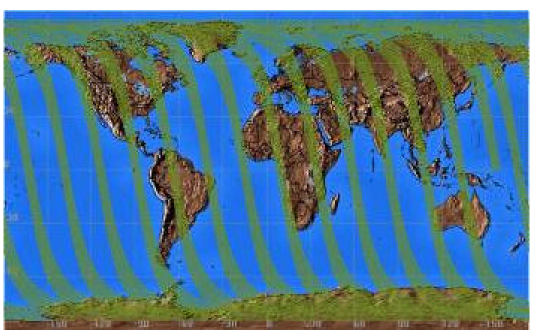

Figure 4 Daily Imaging Coverage of a Single DMC Satellite

By adding satellites to the same orbit, and evenly distributing these around the orbit the additional swaths will fill the coverage gaps. For approximately a 600km swath, 5 satellites are required to provide full global imaging coverage on a daily basis. This is the basic concept for the DMC.

Regional Coverage

Alternatively, if one is interested in regional coverage but at a higher re-visit frequency it is the number of orbital planes that is of importance.

Let us consider, for example, a single satellite able to cover a 600km swath in a 9pm LTAN sun-synchronous orbit. This satellite will provide coverage of approximately 14 to 15 ground-strips per day, each 600km wide and running approximately N-S. This is illustrated in Figure 5 and Figure 6.

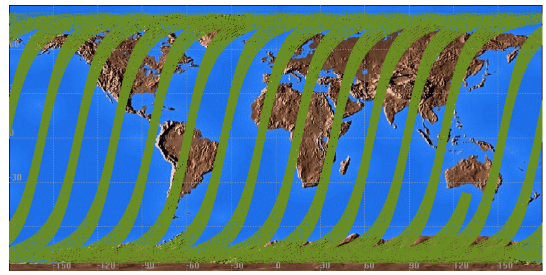

Figure 5 Daily Imaging Coverage of a 600km Swath (Descending Pass)

Figure 6 Daily Imaging Coverage of a 600km Swath (Descending Pass)

The average imaging revisit time for any point on the equator, for example, would be in the order of 5 days, as for the case of a single DMC satellite.

Now consider a constellation of such spacecraft. Rather than adding spacecraft to the same plane, which will image a different ground swath at the same local time (ie. the DMC concept), one can consider adding a spacecraft to the constellation in an identical orbit but with a different LTAN - hence imaging at a different local time.

If the true anomalies are the same then a different ground swath will be covered, at these different local times. This is shown in Figure 7 and Figure 8 for a local time increment of approximately 20minutes and 1hour respectively.

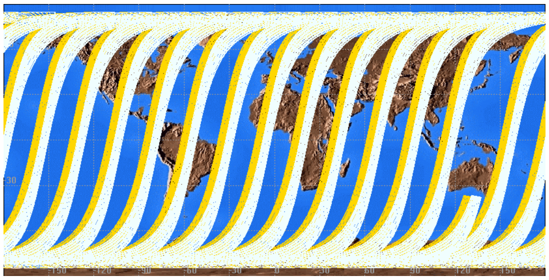

Figure 7 Coverage of Different Ground Swaths with 20minute Local Time Difference

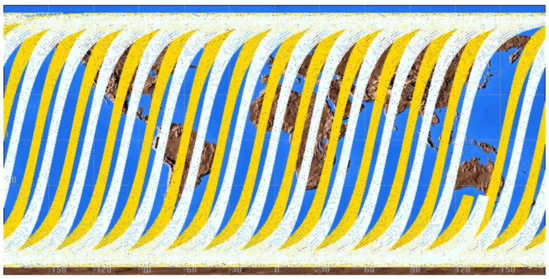

Figure 8 Coverage of Different Ground Swaths with 1hour Local Time Difference

However, it is possible to phase the true anomalies of these spacecraft such that they each cover the same ground track but simply do so at different local times.

Hence, if we have a spacecraft in a 9pm LTAN orbit providing imaging opportunities at approximately 9am ± 10mins, and a spacecraft in an orbit which images on a nadir point e. g, 20 minutes, 30 minutes, 'n' minutes or 'n' hours later (up until e. g. 3pm), then these could be configured to pass over the same area.

Hence the ground track would be as shown below for all of the spacecraft, but each spacecraft images at its respective local time.

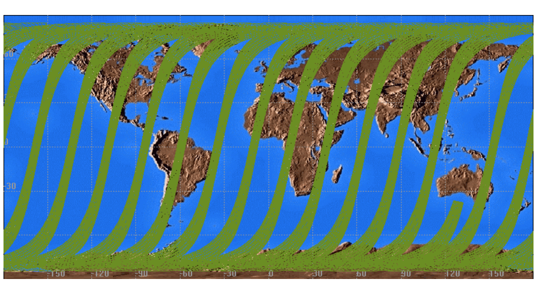

Figure 9 Regional Imaging Coverage from a Constellation of 600km Swath Satellites

This can be scaled simply.

Consider the time of day of approximately 9am until 3pm. If one wanted to provide frequent regional imaging during these hours one could consider a constellation of satellites in sun-synchronous orbits, each with a different LTAN and imaging local time.

Table 1 No. of Satellites vs. Imaging Frequency

No. of Satellites	Frequency of Imaging
3	Every 3 hours e. g. 9am, 12noon, 3pm
7	Hourly; 9am, 10am, …., 2pm, 3pm
20	Every 20minute e. g. 9am, 9:20, 9:40…..2:40, 3pm

It should be noted that in the case of regional imaging with a single satellite per plane then a 1-day repeat orbit is required in order to maintain the same ground track from day to day. Otherwise the region covered from day to day will vary.

Repeat Ground Track

A sun-synchronous 1-day repeat orbit exists at approximately 567km and also at 894km.

There are, of course, a number of considerations that need to be taken into account when considering the application of a spacecraft platform in a variety of altitudes. A detailed consideration would need to be made when selecting the exact platform solution chosen for the mission.

However, an important constellation specific, rather than platform specific, consideration is the number of satellites needed for the desired coverage. To allow comparison, the DMC 32m imager geometry is assumed and referenced in Table 2.

Table 2 Considerations for 1-day Repeat Orbits

Orbit Altitude	Considerations
567	Smaller GSD, ~26m at Nadir
	Reduced swath width of imager means 6 satellites per plane are required for global coverage (assuming DMC imager geometry)
	Increased atmospheric drag, hence reduced lifetime or additional propellant required for same lifetime
894	Greater GSD, ~41m at Nadir
	Increased swath width means 4 satellites are able to provide global coverage (assuming DMC imager geometry)
	Increased radiation environment would need evaluation

Coverage of Larger Regions

In order to increase the size of the region covered there are two options: increase the size of swath (or off-pointing capability e. g. for high resolution missions), or add further spacecraft to the plane.

It is always an option to engineer a solution with a wider swath but there are not insignificant engineering challenges in this. Also, the demands placed on the spacecraft design increase as the swath width for a spacecraft imaging payload increases, adding cost and complexity to the solution. An increased off-pointing angle should be evaluated on a case-by case basis depending on imager and image quality requirements.

For the purposes of illustration of what may be achieved with current designs this paper considers the latter option. If a spacecraft is added to the same orbital plane then an additional 600km swath may be imaged. This may be phased such that it is directly adjacent to (actually slightly overlapping to guarantee no gaps) the first 600km swath and hence providing an approximately 1200km swath as shown in Figure 10 and Figure 11.

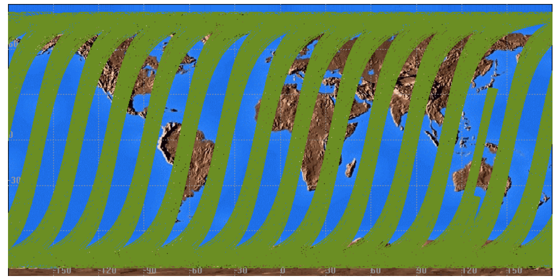

Figure 10 Double Swath Regional Imaging

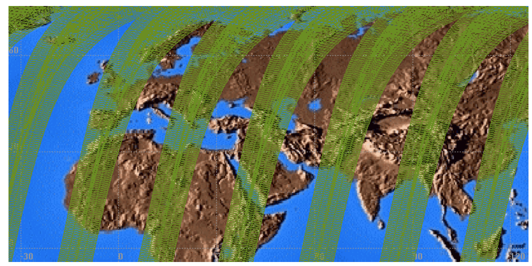

Figure 11 Double Swath Regional Imaging (close-up)

Alternatively the additional satellite may be phased such that a different selected swath is imaged as shown in Figure 12.

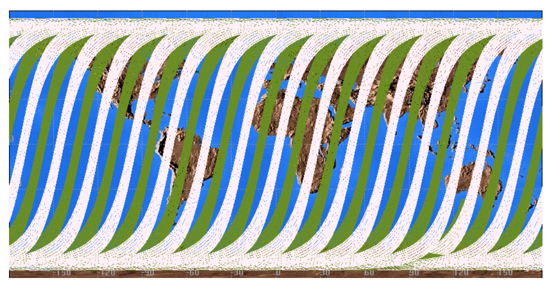

Figure 12 Multiple Swath Imaging

It should be noted again that in order to image the same region, at the same selected local times every day a 1 day repeat orbit is necessary.

For a direct comparison, the DMC imager geometry the approximate swath width at the 567km and 894km repeat orbit altitudes is approximately 530km and 830km respectively.

Global Coverage at Increased Frequency

The requirement of the repeat orbit as described above is the case until one reaches the correct number of satellites per plane to provide global coverage as shown in Figure 13.

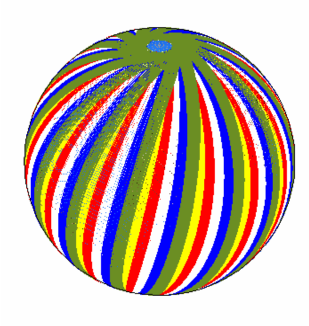

Figure 13 Global Coverage

As soon as this is the case, it does not matter if a one day, 5-day or n-day repeat orbit is chosen, as the entire globe will be covered every day at the times of day chosen for the orbits. This allows more flexibility in orbit altitude choice and such break points as described in Table 3 should be considered in altitude selection (note that this is assuming use of the same imager geometry as for the DMC).

Table 3 Altitude vs no of Satellites

Orbit Altitude (approx)	Considerations
>650km	~30m at Nadir
	Provides full global coverage with 5 satellites/plane
>800km	~37m at Nadir
	Provides full global coverage with 4 satellites/plane

However, in the non-repeat orbit (1 day), which satellite images which region will vary from day to day.

Technically, it is possible to provide global coverage on an orbital period basis with a constellation of satellites imaging at different local times, but phased with the same true anomaly, rather than phased to cover the same region. In this case, with approximately a 600km swath, 20 satellites in 20 orbital planes spaced approximately 20minutes apart would create an effective 12000km swath coverage per orbit, (covering everywhere on the Earth's surface that is between the hours of approximately 9am and 3pm). However, this same result can be achieved with less planes of satellites and more satellites per plane which is typically more cost effective to launch.

Summary of Imaging Coverage Examples

It can be seen that a number of LEO constellation options exist for either global coverage or regional coverage. The geographical scale and/or frequency of imaging revisit depends on the number of satellites. For coverage of a greater area, in general, the number of satellites per plane is most important. For coverage at a greater frequency the number of planes is of most importance.

Local Time Limitations

The above sections describe constellations providing imaging coverage throughout local times from approximately 9am until 3pm. Although SSTL has acquired good quality images at times beyond these, they are assumed in this paper as a safe example of local time boundaries within which good quality images may be obtained with the DMC type imager.

It should be noted however, that the higher resolution imagers such as the 4m or 2.5m option will typically have a smaller window of local time in which imaging can be achieved, for example, between 10-2pm or 11-1pm, if being more conservative. Beyond these times of day, the image quality may substantially reduce. Of course the level and nature of image quality required depends on the application hence, strict limits cannot be discussed in this paper. However, such limitations should be borne in mind.

Bearing such limitations in mind one might consider, for example, a constellation that images at 20-40m every 'n' minutes between 9am and 3pm each day, but that also has a number of imaging opportunities at high resolution (e. g. 3-4m GSD) between the hours of 11am and 1pm, or 10am and 2pm.

Communications Access

If interested in rapid imaging revisit, then one should also be concerned with communications to command image tasks and receive image data. For a sun-synchronous orbit discussed here, a high latitude ground station may provide a communications opportunity on every orbit, or approximately every 100minutes.

This would allow the satellite to receive a schedule of imaging commands just as it begins its sunlit imaging pass on each orbit. The images taken in that orbit could be stored and downlinked to the high latitude ground station on the next pass.

Alternatively if interested in regional imaging only it may be more appropriate to have a receive ground station based in the region for a near real time service.

Taking this a little further it may be of use to have a command and receive ground station in the region of interest, to provide the opportunity for deciding exactly which area to image even closer to the event.

Hence, we can see that there are a number of options that allow an increasing performance in system response time.

Low-medium Inclination Options

Lower inclination constellations were considered. It can be seen that with a 600km swath coverage full longitudinal coverage can be achieved every day by a single satellite in an orbit of approximately 15° inclination, and hence covering latitude bounds ±15°. With 2 satellites in the same plane, full coverage can be achieved within latitude bounds ±20°, 3 satellites give approximately ±35°, and 4 satellites give daily coverage for approximately ±50° latitude bounds.

However, it should be noted that these are maximum latitude bounds. The non-sun-synchronous nature of the orbits means that at different times of the year the LTAN will differ. When considering an imaging constraint of 9am to 3pm this varies the latitude coverage as the spacecraft will be at different latitudes between these local times at different times of year.

An example is shown below for the ±50° case.

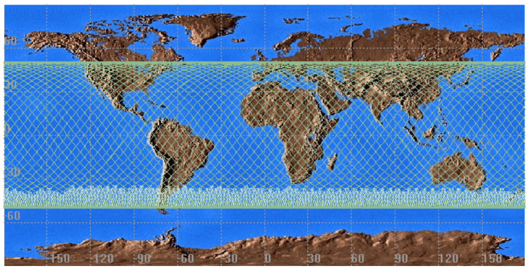

Figure 14 Daily Coverage with 6pm LTAN

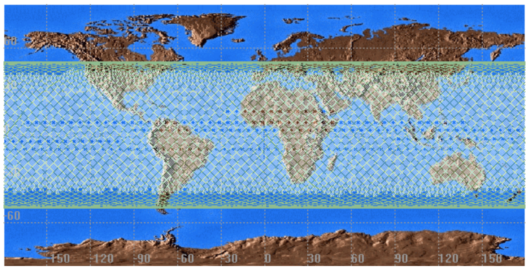

Figure 15 Daily Coverage with 12pm LTAN

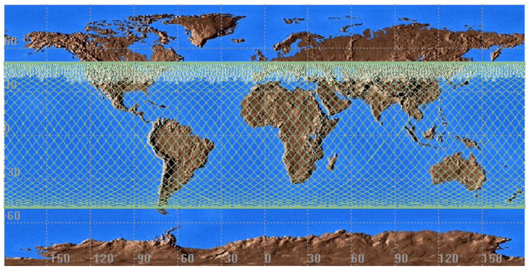

Figure 16 Daily Coverage with 6am LTAN

Another possible drawback with the lower inclination orbits is that it is not possible to have access to a high latitude ground station, capable of providing communications access every orbit as already discussed. Hence, unless satellite communications occur locally within the monitored region, either a complex ground infrastructure is needed, or inter-satellite links must be introduced for a rapid response system.

For these reasons the low inclination options are not considered further here. However, if one is interested only in near equatorial regions this option should not be discarded.

Other Orbit Options

This section highlights some of the main considerations for potential ‘rapid imaging’ solutions other than circular LEO constellations.

Geo-stationary orbit provides an obvious candidate for high temporal resolution imaging, as demonstrated by existing weather satellites. However, when considering options of imaging at 4m GSD or smaller, it is clear that the engineering of such an imager for GEO is a massive and costly task. The spacecraft platform to support this would also be complex and large. The technical risks involved in such a development would be high and the concept of redundancy and graceful degradation available in a LEO constellation scenario is not available.

MEO orbits are another option that may be investigated in the number of satellites/satellite cost vs. launch costs trade-off. Again the same issue arises as for GEO, the high altitude generally leads to a requirement for larger and more expensive platforms to support larger, more expensive payloads if the same GSD requirement is considered. Typically, when one considers the benefits of a higher altitude one considers the resulting increase in coverage due to a swath increase. However, if the same GSD is required as at a lower altitude then the same swath will be obtained with the same number of pixels, but with larger optics. Hence, many of the engineering issues for the payload are not dissimilar to engineering a larger swath for a LEO spacecraft, except with larger optics.

Of course other platform trades exist including the attitude control and off-pointing capabilities, and a detailed study of MEO design solutions would need to be made before making the LEO/MEO trade off.

One more orbit option is that of eccentric orbits. These allow a greater proportion of time to be spent over the regions that are beneath the spacecraft apogee at any point in time, and hence should certainly be considered for regional imaging solutions. The position of the apogee (and hence sub-apogee region) will vary unless the orbit is at the critical inclination of 63.4°. This inclination gives the same problems for an imaging mission, however, as described earlier for other low inclination orbits, ie. a varying local time will be had at different latitudes throughout the year. Also, the higher altitude above the region of interest leads to the same issues of larger more expensive platforms as described for MEO/GEO orbits, and the varying altitude and ground velocity throughout the orbit introduce other engineering issues for the spacecraft.

The above gives an idea of some of the issues involved. Of course, for specific applications all orbit options should be considered in the early stages of the mission design. However, the above issues, along with the fact that much experience exists in LEO imaging missions leads towards a preferred approach of small satellite LEO constellations using existing small-satellite technology or incremental developments to existing technology.

Launch Strategy

The optimisation of a constellation strategy depends on the launch cost (per satellite) vs. satellite cost as well as the total number of satellites. Hence, the possible accommodation of satellites in available launch vehicles should be considered carefully in the early stages of mission design to ensure the most appropriate path is taken.

For the purposes of presenting some example costs here, 5 satellites per launch are assumed. The number of satellites that may be accommodated on a launcher will vary, of course, depending on the actual satellite platform chosen, launcher and launcher multiple accommodation strategy.

Of particular significance when considering launch strategy is the number of satellites per plane. Typically, with current propulsion technology, it is necessary to use a separate launch for each plane desired. Hence, a single 5-satellite launch may not be used for a 5-plane/5-satellite system. However, accommodation permitting, a single launch may be used for a 5 satellite-single plane system.

It should be noted however, that advancements in propulsion technology may allow some multiple plane systems to share a launch. This is discussed briefly later in the paper.

SSTL has launched 19 satellites on shared launches and also has recent experience in working with launch authorities for the DMC mission in designing accommodation for multiple small satellites on multiple shared launches for a constellation scenario.

Replenishment Strategy

The constellation approach provides a graceful degradation scenario in the event of a satellite failure or simply reaching the end-of-its life. The replacement strategy should attempt to launch the highest number of satellites/launch for maximum launch cost effectiveness. For this reason, the allowable degradation in coverage before any one satellite must be replaced should be carefully considered.

Relative Costs

The pie charts in Figure 17 and Figure 18 below indicate the proportion of costs between a dedicated launch per satellite and a case where one is able to launch 5 satellites on the same launch. If we consider the basic premise that, whether temporal or geographical scale, more satellites give better coverage it is obvious that more satellites/launch is more cost effective.

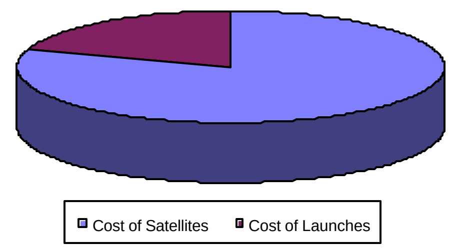

Figure 17 Five Satellites per Launch

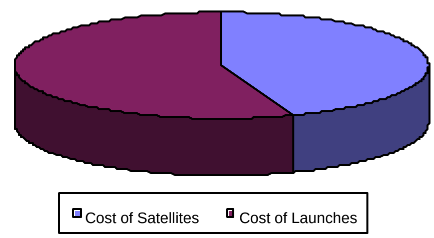

Figure 18 One Satellite per Launch

However, it is important to bear in mind break points such as how many satellites per plane are needed for full global coverage. It is also important to bear in mind that the ultimate judgement should be made not on proportion of costs between satellites and launch, but the total cost required to meet a given application.

To give an idea of what might be expected some approximate satellite and launch costs for different systems are listed in Table 4. This table assumes 8M USD per satellite and 10M USD per launch as fixed costs for comparison. Note however that the satellite costs and cost per launch would vary from this depending on the satellite platform and launch negotiation for the mission but the table should serve to give a feel for relative costs between the systems.

It should be noted that the table assumes coverage between 9am and 3pm.

Table 4 Example 'Concept' Costs

Coverage	Revisit Time	Costs (mUSD)
Global	Daily	50
Global	3hours	150
Global	1hour	350
Global	20mins	1000
Regional (600km Swath)	20mins	360
Regional (2 x 600km Swath)	20mins	520
Regional (600km swath)*	20mins	250

*assuming enhanced propulsive capability, allowing 3 satellites to share each launch (see later in paper)

Other options

This paper has discussed various limitations on a mission such as VISTA with current technology. There are, however, several areas that stand out as potential areas of improvement.

Wider Range of Local Times

As has been mentioned already, the local times at which optical imaging can occur are generally constrained to between 9am and 3pm for moderate resolution and 10 or 11am until 1 or 2pm for high resolution.

Whilst imaging may occur beyond these times, the image quality will be reduced as illumination conditions worsen. Many real-time applications require simply visually intelligible imagery, and there is not a strict cut-off point for such a definition without a specific application definition.

Typically specific applications for imaging early in the morning or late in the afternoon have not been drivers for imager designs at SSTL. However, such options may be investigated for missions such as VISTA in order to increase the timespan of coverage each day.

Improved Propulsion Capability

On-going propulsion research and development at SSTL is hoped to result in significant advances in the DeltaV capacity that can be provided for an enhanced microsatellite platform.

The current DMC system uses butane propellant. This would likely be the choice for DeltaV capabilities of 10 to 20m/s. However, current SSTL research into new propellants is expected to offer, for a similar sized system, DeltaV capabilities of 50m/s and even in excess of 100m/s.

Such improvements in micro-satellite propulsion technology open up new possibilities for shared launches for spacecraft destined for different orbit planes, and hence potentially large launch cost savings.

For example, consider a single launch of three satellites to the same plane. Each satellite may add to the ground area coverage in this plane. However, the improvements in propulsion would allow these satellites to adjust their inclination or altitude to introduce an LTAN drift. These satellites may then be allowed to drift over a period of time until 'on-station' in their respective target LTANs. The prospective propulsion capabilities referred to above would enable this to occur for small LTAN drifts of e. g. 20 minutes within the first year of the mission. Hence the mission would begin with a baseline level of service and gradually move towards the next plateau as the spacecraft drifted to their target orbits.

Synthetic Aperture Radar

SSTL has performed studies on the feasibility of small satellite SAR missions. Whilst there is not an off-the-shelf small satellite SAR solution existing, this should be considered a future area with many possibilities. The use of SAR removes the local time restrictions discussed earlier for optical imagery.

Conclusions

This paper has illustrated that the possibility of multiple satellite constellations, which are made affordable by the application of small satellite technology, and selection of the appropriate orbit configuration, rapid imaging revisit can be achieved on a regional or a global scale.

SSTL are already pioneering this field with the DMC mission, providing a global imaging revisit capability on a daily basis. This concept can be scaled to provide global imaging revisit on an hourly, 30minute, 20minute or ‘n’ minute interval within reasonable imaging times of day (e g. 9am to 3pm for moderate GSD, 10 or 11am to 1 or 2pm for high GSD). Regional imaging may be achieved similarly with fewer satellites.

The total cost of any system put up depends on the total number of satellites and the number of satellites per launch. This introduces certain break points in a cost model (e. g. one extra satellite may lead to an extra launch) and any requirements that lead to a transition of these break points should be carefully studied and justified.

Whilst the requirements for the number of satellites in the constellation should be carefully monitored, multiple spacecraft are generally required to provide higher temporal resolution and there is a simple rule: the more spacecraft, the higher the imaging revisit frequency. The costs associated with large platforms, and their launch, are prohibitive in providing constellations of a significant number to provide really rapid imaging revisit.

It is in this area that small satellites have the potential to open up opportunities that have previously been considered unrealisable.

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