Small Satellites in Inclined Orbits to Increase Observation Capability Feasibility Analysis

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Abstract

Over the period of past four decades, Remote Sensing data products and services have been effectively utilized to showcase varieties of applications in many areas of resources inventory and monitoring. There are several satellite systems in operation today and they operate from Polar Orbit and Geosynchronous Orbit, collect the imagery and non-imagery data and provide them to user community for various applications in the areas of natural resources management, urban planning and infrastructure development, weather forecasting and disaster management support. Quality of information derived from Remote Sensing imagery are strongly influenced by spatial, spectral, radiometric & temporal resolutions as well as by angular & polarimetric signatures. As per the conventional approach of
having Remote Sensing satellites in near Polar Sun synchronous orbit, the temporal resolution, i.e. the frequency with which an area can be frequently observed, is basically defined by the swath of the sensor and distance between the paths. It has been proved earlier with several international missions that it is possible to increase the observation capability by launching the satellites in inclined orbit. An example of such Indian mission is Megha-Tropiques satellite, which was an Indo-French Joint Mission, launched in a circular orbit with 20 degree inclination.

Though the advantages of inclined orbits for frequent revisit remain same for any satellite launched in these orbits, small satellites provide additional advantages in terms of faster realisation, formation of constellation to enhance the observation capability at low cost. The paper addresses some possible mission scenarios to cover the entire Indian region and coastal region for land and water as well as for coastal applications. The study also addresses the Pros and Cons of having small EO satellites in inclined orbits and also the possible payload choices.

**Key Words:** Remote Sensing; Temporal Resolution; Swath; Inclined orbit; Small Satellites

1 Introduction

Earth Observation (EO) from space has proved its immense potential for providing valuable information on natural resources and environment on various spatial, spectral and temporal scales. The Indian Space Research Organisation (ISRO) has launched a series of state-of-the-art remote sensing satellites catering to the needs of various thematic applications since the launch of first operational Remote Sensing satellite, IRS-1A, in the year 1988. The data from these EO satellites have been used in the areas of agriculture, water resources, forestry and environment, urban planning and rural development, utilities planning and infrastructure development, watershed development, geosciences and mineral prospecting, cartography and large scale mapping, as well as oceanography and meteorological applications. The INSAT series of satellites, with meteorological payloads operating from geostationary orbit, pro-
vides necessary data for various meteorological applications.

Observational strategy is linked to the scale of process of studies which varies in spatial as well as temporal scales. It is also to be noted that terrestrial processes are slower as compared to oceanographic and atmospheric processes. Accordingly, the Earth Observation or Remote Sensing satellites are generally launched in Low Earth Orbit (LEO), and Meteorological satellites are placed in Geo Stationary Orbit (GEO), providing data every half-an-hour for various meteorological applications. One of the major distinctions in the image data provided by LEO and GEO orbit lies in the spatial resolutions. Whereas data acquired for earth resources purposes from LEO generally has pixel sizes of less than 100 m, that used for meteorological purposes (both at geostationary and lower altitudes) has a much coarser pixel, often of the order of 1 km (Richards and Jia, 2006).

On October 12, 2011, ISRO has launched Megha-Tropiques satellite, into a circular orbit with 20 degree inclination to the equator. It is an Indo-French joint satellite mission for studying the water cycle and energy exchanges in the tropics. The main objective of this mission is to understand the life cycle of convective systems that influence the tropical weather and climate and their role in associated energy and moisture budget of the atmosphere in tropical regions. It provides scientific data on the contribution of the water cycle to the tropical atmosphere, with information on condensed water in clouds, water vapour in the atmosphere, precipitation, and evaporation. Considering that the requirement of repeated observation over the tropical region, the satellite was launched into an inclined orbit and the repetivity of the satellite is about 3-8 times a day.

The space based applications over the period of time have become multi-fold in diversified areas and even for terrestrial applications, the demand for repeat observations has increased. Some of the important applications which demand frequent observations are target identification and Area of Interest (AoI) coverage, monitoring of right of usage area over gas and oil pipelines, mining alert, coastal area observation, continuous monitoring of cyclone track, its intensity and landfall, rapid assessment of damage due to disasters, and temperature and humidity profile in the tropical region for weather prediction and forecast.
As reported by Satellite Industry Association, small satellites and miniaturization has continued and growing interest amongst the global community (SIA, 2015) considering its advantages in terms of faster realisation, formation of constellation to enhance the observation capability at low cost. Realising the missions in small satellite is also one of the solutions to meet the gaps in observation. Considering the importance, ISRO also conceived the small satellite programme and already realised a few satellites on a small satellite bus namely IMS-1 (TWSAT), Youthsat and SARAL.

2 Feasibility Study

Analysis has been carried out to improve the temporal resolution for EO satellites in Low Earth Orbit and described hereunder.

2.1 Sun-Synchronous Orbit

There are essentially two broad classes of satellite programs: those satellites that sit at geostationary altitudes above the earths surface and which are generally associated with weather and climate studies, and those which orbit much closer to the earths surface and that are generally used for earth surface and oceanographic observations. Usually, the low earth orbiting satellites are in a Sun-synchronous orbit, in that their orbital plane precesses around the earth at the same rate that the Sun appears to move across the Earths surface. In this manner the satellite acquires data at about the same local time on each orbit (Richards and Jia, 2006). The basic property of such type of Sun-synchronous orbit is that it keeps the angle of sunlight on the surface of the Earth as consistent as possible, though the angle changes from season to season. This consistency means that scientists can compare images from the same season over several years without worrying too much about extreme changes in shadows and lighting, which can create illusions of change. Figure-1 shows altitude verses inclination graph for Sun-synchronous orbit. As can be seen from the graph, for the altitudes below 1000 km, the orbit inclination is between 97 to 100 deg.
One of the important application requirements considered for the study is to cover the entire coastal area of India as well as entire Indian land mass on a daily basis. As per the conventional approach of having Remote Sensing satellites in near Polar Sun synchronous orbit, the temporal resolution, i.e. the frequency with which an area can be frequently observed, is basically defined by the swath of the sensor and distance between the paths.

Figure 1: Altitude verses inclination graph for Sun-Synchronous Orbit

Figure 2: Ground Trace of Sun-Synchronous orbit at altitude 720 km with 2-days repeat cycle
Let us consider a payload with swath of 1400 km, like in the case of Ocean Color Monitor (OCM) of Oceansat-2, at an altitude of 720 km and inclination of 98.24 deg. The ground trace pattern for this orbit is shown in Figure-2, and the repeat cycle for this orbit is 2 days. With one satellite, the whole Indian coverage is possible in 2 days. With the constellation of two satellites, whole coverage is possible in one day. The number of day-time passes will be 3-4 and the number of night-time passes will be 3-4 and the total visible passes per day will be about 6-8.

Now, let us consider a payload with a swath of 20 km like in the case of high resolution satellites. For lesser swath, the repeat cycle increases for systematic coverage, but the coverage for any specified area can be done with better revisit by tilting the spacecraft towards the target. The satellite is said to be accessible with respect to the target or ground station if the slant angle towards the target is lesser than the 0.5 x Earth Subtend angle i.e. 65 deg at an altitude of 630 km. In this scenario, the number of day-time passes will be 2-3 and the number of night-time passes will be 2-3 and the total visible passes per day will be about 4-5. But for imaging application using optical data, the tilt angle is restricted to 26 deg to 45 deg. Therefore the revisit duration depends upon the maximum tilt allowed on the spacecraft. With the restricted tilt angle, the satellite can image the target only once out of 5 accessible orbits. The imaging opportunities at 630 km altitude are given in Table-1. It can be observed from the table that with a proper constellation of 3 satellites, the revisit of any specified area can be improved to around 24 hrs if the tilt capability can be up to 45 degrees. With a moderate tilt say 26 degrees, the revisit will be everyday with a constellation of 4 satellites. With the usage of radiometers or illumination independent payloads, the revisit can be improved to 12 hrs.
Table-1: Imaging Opportunities at 630 km altitude

<table>
<thead>
<tr>
<th>Altitude</th>
<th>No of satellites</th>
<th>Average Revisit @ Equator(day)</th>
<th>Tilt requirement in degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>630 km</td>
<td>1</td>
<td>4.5 (4 to 5)</td>
<td>25 deg</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2.25 (2 to 3)</td>
<td>45 deg</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.25 (2 to 3)</td>
<td>25 deg</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.12 (1 to 2)</td>
<td>45 deg</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.5 (1 to 2)</td>
<td>25 deg</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.75 (~24 hrs)</td>
<td>45 deg</td>
</tr>
</tbody>
</table>

As shown in Figure-1, one can also achieve Sun synchronous orbit with the inclination of around 150 deg at an altitude above 5300 km. Due to increase in altitude, the orbit period is around 200 minutes. Out of total 7 orbits, 2 orbits cover Indian region. The total visible duration also increases up to 28 mins. This orbit does not provide better revisit but the duration of imaging can be more for 1 or 2 orbits over Indian region.

2.2 Inclined Orbits

One of the ways to overcome the limitation of covering the Indian regions with payloads of lesser swath is to have them in inclined orbit. When the payload/spacecraft is positioned in inclined, the orbit could be either recurrent or non-recurrent orbit. A recurrent orbit means that after a certain number of limited days say 1 or 2, the satellite repeats its original orbit. The advantage of high frequency recurrent orbit over low frequency recurrent orbit is that it enables the satellite to observe the same area with better temporal resolution. These intervals are decided by the actual payload application and its swath. Once the interval and swath are defined, the orbit altitude is derived and the inclination is arrived at. With the swath of 1400 km at an altitude of 814.5 km and an inclination of 16.5 deg the Indian coastal region can be covered as shown in Figure-3. The Indian region can be covered with an inclination of 26 deg at an orbital height of 814.5 km with the swath of 1400 km and a roll bias of 45 deg as shown in Figure-4.
For high resolution payloads, the tilt requirement depends upon the placing of the target with respect to actual paths. For a target in-between two tracks at the latitude of inclination, the tilt requirement is shown in Figure-5. Also the local time at feasible tilt values is also depicted along with tilt requirement for a typical case (altitude 630 km, inclination: 20 deg). For such an observation at a latitude equivalent to inclination, a single spacecraft can provide two opportunities, worst case both can be in non-sunlit duration.
The feasible tilt is marked in black. The total number of passes within the feasible tilt is 2. Out of these 2 passes, both passes are out of range 8 AM to 4 PM. But with the constellation of 3 satellites, at least one pass per day will fall in illumination. This indicates that for high resolution and lesser swath (¡ 20 km) payload, the constraints of illumination condition and feasible tilt capability restricts the number of accessible passes but it provides good revisit coverage for broader swath (¡ 700 km) for optical payloads and also for microwave payloads which are illumination independent.

2.3 The Sun aspect angle variation

As the orbital regression rate for low inclined orbit is around -6.4 deg/day, the Sun-aspect angle undergoes a wide variation as shown in Figure-6, with the cycle time of around 52 days. The local time variation due to the Sun aspect angle variation is shown in Figure-7.

Figure 6: Sun aspect angle variation in low inclined orbit

Figure 7: Local time variation over a cycle of 52 days
Due to day-to-day variation of local time of about 30 minutes shift/day, the most suitable payloads for such an orbit are those which are independent of Sun-illumination such as radiometers, microwave payloads, IR payloads etc. For optical payloads, if the local time range is 8 AM to 4 PM, the suitable orbits satisfying this range are depicted in Figure-8 for an inclination of 20 deg.

![Figure 8: Passes in suitable local time for one satellite (Inclination: 20 deg, asn: North Bound passes, dsn: South bound passes)](image)

Figure 8: Passes in suitable local time for one satellite (Inclination: 20 deg, asn: North Bound passes, dsn: South bound passes)

Figure-9 depicts the average number of such passes over a day for a typical orbit with inclination of 20 deg. It is evident from the figure that the number of suitable passes, out of 6-7 orbits, varies from 1 to 5. There is a certain period (around 14 days) when all passes lie during night time.

![Figure 9: Average number of passes in a cycle for suitable local time](image)

Figure 9: Average number of passes in a cycle for suitable local time
2.4 Constellation of satellites

To avoid the gaps for imaging in the suitable local times, three satellites with appropriate phase difference in Right Ascension of Ascending Node, can be grouped as a constellation. It is can be observed from Figure-10 that the number of passes within 8 AM to 4 PM is 5 to 7 over Indian Region. The launch of three satellites needs to take place at different local times (Relative local time difference: 8 hours). Otherwise fuel called for is exorbitant to take these planes separation post launch.

![Figure 10: Number of passes in suitable time with 3 satellites phased at 120 deg](image)

2.5 Small Satellites Constellation

Small satellites are becoming increasingly popular due to their low cost, minimized volume and reduced design and development time. However, they fulfill all the necessary objectives of a space mission. Small satellites are globally preferred due to achieving more missions within fixed budgets, reducing the time to get into orbit (faster development time), making constellations and formation flying financially viable. ISRO has developed two types of Small Satellite Buses namely Indian Mini Satellite-I (IMS-I) and Indian Mini Satellite-II (IMS-II) and the brief specifications and capabilities of these buses are given in Table-2:
Table-2: Major Specifications and Capabilities of Small Satellites Buses of ISRO

<table>
<thead>
<tr>
<th>Major Feature</th>
<th>IMS-1</th>
<th>IMS-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>100 kg class</td>
<td>450 kg class</td>
</tr>
<tr>
<td>Max. Bus Mass &amp; Payload Mass</td>
<td>70 kg &amp; 30 Kg</td>
<td>250 kg &amp; 300 Kg</td>
</tr>
<tr>
<td>Outboard Propellant</td>
<td>3.5 kg</td>
<td>21 kg</td>
</tr>
<tr>
<td>Redundancy</td>
<td>No Redundancy</td>
<td>Full Redundancy</td>
</tr>
<tr>
<td>Design Lifetime</td>
<td>2 year</td>
<td>5 year</td>
</tr>
<tr>
<td>RAW Bus</td>
<td>28-33 V</td>
<td>28-33 V</td>
</tr>
<tr>
<td>Solar Array Power @ BOL</td>
<td>230 W</td>
<td>675 W (850W BOL)</td>
</tr>
<tr>
<td>Payload Power:</td>
<td>30 W Continuous / 70 W in Duty Cycle</td>
<td>250 W Continuous / 600 W in Duty Cycle</td>
</tr>
<tr>
<td>Attitude Control :</td>
<td>3-axis stabilized with Reaction wheels</td>
<td>3-axis stabilized with Reaction wheels / RCS</td>
</tr>
<tr>
<td>SSR Storage</td>
<td>16 Gb</td>
<td>32Gb (SDRAM) / 256Gb (Flash Memory)</td>
</tr>
<tr>
<td>Payload Data Storage &amp; Downlink</td>
<td>≤ 10Gbits storage: ≤ 5 Mbps DL, nre</td>
<td>≤ 330Gbits storage: ≤ 595 Mbps DL, nre</td>
</tr>
<tr>
<td>Missions Launched</td>
<td>IMS-1 (TWISAT), IMS-1A (YOUTHSAT)</td>
<td>SARAL</td>
</tr>
</tbody>
</table>

3 Discussion

One of the important criteria which demanded the feasibility of inclined orbit is the requirement for Indian area coverage, especially Indian costal area coverage on a daily basis. As Indian latitudes of interest spread over the range from below equator 45 deg to about 45 degrees, different approaches for constellation population has to be followed to get better temporal revisits. The important outcomes of the study are (i) entire Indian coastal region can be covered with the swath of 1400 km at an altitude of 814.5 km with an inclination of 16.5 deg and (ii) the Indian region can be covered with an inclination of 26 deg and orbital height of 814.5 km, swath of 1400 km with a roll bias of 45 deg. As discussed earlier, the area of coverage varies with swath of the payload.

In the low inclined orbit, the Sun-aspect angle undergoes a wide variation due to orbital regression rate. For optical payloads, imaging time is very important and suitable time for imaging is from 8 AM to 4 PM. In the inclined orbit, day-to-day variation of local time is observed. Hence, the number of possible orbits in a day, with 8 AM to 4 PM passes, varies from 1 to 5 and there are certain periods where all passes would be in the night time. Hence, in order to overcome the gaps in observation, one need to think of a minimum of three satellite constellation so that there are at least 5 to 7 passes, every day. Or alternately Sun-synchronous orbits with the same number of constellation members will also meet the
requirements, in addition to giving option of coverage of the total globe.

In order to realise the constellation at low cost and at a faster, small satellite offers a better solution. The existing IMS-1 can support payload of 30 Kg and provide 30W continuous power and 70W in duty cycle. On the other hand, IMS-2 can support payloads of 200 kg and provide 250W continuous power and 600W in duty cycle. Hence, it is a good platform to host payloads like Panchromatic (1m resolution) and Multispectral cameras (4m resolution), Hyperspectral sensors, Scatterometer, Altika, Temperature and Humidity Sounder, etc. ISRO has already flown Altika in SARAL mission and Ku-band scatterometer is being planned onboard Scatsat-1 mission on IMS-2 platform.

Considering that Sun aspect angle and local time variations are bound to vary for every orbit, analysis on Bidirectional Reflectance Distribution Function (BRDF) is critical for optical payloads. Signal strength, noise and hence the Signal to Noise Ratio (SNR) also varies over the imaging times. Hence, a detailed analysis on BRDF is needed for the correction of view and illumination angle effects (for example in image standardization and mosaicking) and for deriving albedo.

4 Conclusion

Remote Sensing satellites are generally launched in near polar Sun Synchronous orbit. The repeat coverage over the same area is determined by the swath of the sensors and the distance between the paths. Hence, the repeat coverage or repetivity of the High Resolution satellites are of the order of 150–200 days and hampers the temporal data requirements of users. One of the approaches to meet the temporal requirements is to have the satellite in the inclined orbit as discussed in this paper. While polar orbit satellites meet global coverage requirements at the cost of temporal resolution requirements, inclined orbit satellites meet region specific coverage requirements. However, the inclined orbit has limitation for optical payloads in terms of number of passes available during 8 AM to 4 PM, suitable for imaging, which calls for constellation of satellites. However, for microwave payloads, which do not depend on
the Sun illumination, inclined orbit is a good solution for temporal requirements. In order to meet the temporal requirements of high resolution data, constellation of satellites needs to be planned and for optical payloads as well as a detailed analysis on BRDF needs to be carried out. It is also possible to achieve Sun synchronous orbit with the inclination of 150 deg at an altitude above 5300 km. Due to increase in altitude, the orbit period is around 200 minutes and 2 orbits would cover Indian region and the visible duration increases to 28 min. As the swath of high resolution missions are limited, some satellites in higher altitudes need to direct high resolution missions where imageries are to be collected at the region of interest. Though this orbit does not provide better revisit, the duration of imaging can be more for 1 or 2 orbits over Indian region.

5 Acknowledgements

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