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Deriving Primary Specifications of Optical Remote Sensing Satellite from user Requirements

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Abstract*: *Remote Sensing is a technique applied to collect information of targets including Earth by acquiring images in selected spectral bands. Satellites are used as remote sensing platforms as they provide numerous advantages like wide area imaging, systematic coverage etc. Low Earth Orbit (LEO) polar satellites are preferred for the remote sensing applications as they provide global coverage. The images acquired through satellite remote sensing are used for many applications such as cartography, agriculture, limnology, oceanography, environmental study, forestry, geology etc. Applications dictate primary specifications of observation instrument and satellite orbital parameters.

This paper presents the steps involved in deriving primary specifications of imaging optical payloads and orbit parameters for systematic coverage from user requirements. Some of primary system specifications are such as camera focal length, field of view, aperture size, number of bands, band width, detector size, quantisation bits, altitude, revisit time etc. Primary system specification are derived from four different resolutions namely, temporal, spatial, radiometric and spectral resolution. These resolutions vary with the applications. These primary specifications help to derive the specifications of satellite subsystems like data handling system, power system, communication system, Attitude and Orbit Control System(AOCS), Structure, Thermal Control System(TCS) etc. A computer program was developed in MATLAB to generate different parameters based on user requirements. These parameters will be specifications for subsystem design. Few case studies have been carried out and results were analysed.

Index Terms*: *Satellite, Remote sensing, Orbit, Altitude, Sensor, focal length.

I. INTRODUCTION

Remote sensing is science and technology which collects information of the targets without having physical contact with them. Ground based sensors use acoustic, electromagnetic, magnetic field for remote sensing. The space based remote sensing uses the electro-magnetic radiation (EMR) due to its capability of travelling in vacuum[1]. Optical imaging sensor is an electro-optical system which collects radiation emitted or reflected by the object, converts into electrical signal and records signal particularly in digital form. The carrier or the vehicle for the remote sensing sensor is generally called as platform. In eighteenth and nineteenth centuries, hot air balloons were used as remote sensing platform. Presently, satellites, aeroplanes, Unmanned Aerial Vehicles (UAV) are extensively used as remote sensing platforms for Earth Observation (EO). The space based systems are preferred among other systems like ground based, aerial data collection systems due to their wide area coverage, systematic and uninterrupted service.

Satellite remote sensing started with the launch of Television Infrared Observation Satellite (TIROS-1) spacecraft on 1st April 1960, which carried a single band TV camera for cloud coverage study. Launch of the Earth Resources Technology Satellite (ERTS-1) carrying multispectral scanner system (MSS) with four spectral bands of 100 nm width and 80 m resolution in 1972, later renamed as LANDSAT-1 is marked as starting of satellite remote sensing for civilian applications like natural resources survey and monitoring[2,3]. While satellites placed in Geo Synchronous Orbit (GEO) provide high temporal resolution and low spatial resolution data, the Low Earth Orbiting (LEO) satellites which are in the orbits with the altitude from 400 km to 1000 km, provide medium and high spatial resolution data. Satellite with less than 400 km altitude faces more drag which reduces the satellite life time and more than 1000 km altitude call for long focal length to get required spatial resolution. For better performance of the satellite data, suitable orbit with appropriate altitude, number of orbits per day, inclination is to be selected.

Users of the remote sensing data provide their requirement in four different resolutions for any specific application. They are namely temporal, spatial, radiometric and spectral resolution. The information content in the remote sensing data depends on these resolutions [4]. These resolutions play an important role in deciding the orbital features like type of orbit, altitude, repeat cycle, swath of the satellite and imaging system parameters like aperture size, focal length, field of view, detector size etc.

The definitions of these resolutions are provided below:

Temporal resolution is defined as number of days between two successive visits of the satellite to the same location. While the repetivity is defined as days between successive visits by the orbit pattern, the revisit is the days between successive visits achieved by orbit pattern and look angles change.

Spatial resolution is smallest object size which can be detected in the image. Smaller the object size, better the resolution. Spatial resolution also can be defined as the projection of pixel on Earth surface.

Spectral resolution is defined as smallest spectral change of the target which can be detected by the sensor. It depends on number of spectral bands and

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bandwidth of the sensor employed. Narrower and much number of bands give better spectral resolution.

Radiometric resolution is defined as the smallest intensity variation that can be detected by the sensor. This is generally represented in the terms of quantization bits covering the dynamic range. More number of bits provide better radiometric resolution.

The resolution requirements vary with interested application[5]. The table-1 presents some important applications and their resolutions requirement.

Table.1. Resolutions Vs Applications

Application	Resolution			
	Spatial (m)	Spectral (Micron)	Radio metric (bits)	Temporal (Days)
Agriculture	25	Mx	10	5
Forestry	70	Mx	8	25
Cartography	<1	PAN	11	90
Ocean	300	Mx	12	1
Disaster Studies	<1	PAN	11	<1

Mx- Multispectral (spectral bands spread in visible and near Infrared)

PAN –Panchromatic

A program in MATLAB was developed to derive the orbital parameters and optical sensor specifications from above said resolutions.

Steps in deriving satellite parameters are as given below.

1. Collect the user requirements.
2. Select suitable altitude to meet the temporal requirement.
3. Derive the inclination requirement to meet the sunsyncronous orbit.
4. Select the equatorial crossing time based on illumination condition requirement.
5. Calculate required swath for the global mission from altitude and the orbit path separation.
6. Compute the Field of View (FOV) of the imaging system from the swath and altitude.
7. Calculate the focal length of the optical system based on the spatial resolution requirement, the selected altitude and detector pixel size.
8. Derive number of bands and the band widths from the spectral resolution.
9. Calculate number of bits per sample from required radiometric resolution
10. Calculate number of pixel from the spatial resolution and calculated swath.
11. Calculate Integration time using the spatial resolution and the ground trace velocity.
12. Compute data rate with number of pixel per band, number of bands, integration time and quantisation bits.

II. DERIVATION OF ORBITAL PARAMETERS

The orbit is a closed/curved path in which satellites or planets travel. Though different types of orbits are possible, for a specific application/requirement, a particular orbit is suitable. The method of deriving relevant orbital parameters to intended remote sensing applications is presented here. Important orbital parameters to satellite remote sensing are,

1. Altitude
2. Inclination
3. Equatorial Crossing Time (ECT)
4. Eccentricity

A. Altitude

The altitude of the orbit is defined as orbital height above the Earth surface and generally mentioned in km which represents the size of the orbit. Generally the remote sensing satellites utilise the Low Earth Orbits (LEO). The orbit pattern of the LEO depends on the altitude and the inclination. The altitude is selected based on the temporal resolution requirement.

The orbit repetition parameter Q a rational number is a summation of an integer number and a fractional part. It can be presented as follow

$$Q = I + \frac{K}{N} \tag{1}$$

Where 'I' is integer number of complete revolutions of the satellite per day,

N is the repeat cycle (in days) which is defined as time difference between two successive visit of satellite to any particular longitude of ascending node[6].

K is integer number 1 to N-1.

If the repeat cycle is one day, ‘I’ will be 14 or 15 for LEO and ‘K/N’ ratio will be zero. However, if repeat cycle is greater than one, the value of orbit repetition parameter will be obtained in fraction.

The orbital time to meet this Q is calculated with following equation

$$T = 1440/Q \tag{2}$$

Where, T is orbital time in minutes.
Q is number of orbits per day
1440 is minutes per solar day.

The semi major axis of the orbit and altitude are calculated with orbital time using following equation[7]

$$a^3 = \frac{\mu T^2}{4\pi^2} \tag{3}$$

Where, a is the radius/semi major axis of the orbit
T is orbital time and

μ = GM is Earth’s gravitational parameter equal to 398,600.4415 km^3/s^2

The relation between Altitude and Orbital Time is shown in the fig. 1. Though the relation is nonlinear, for a small range of altitude it looks like linear.

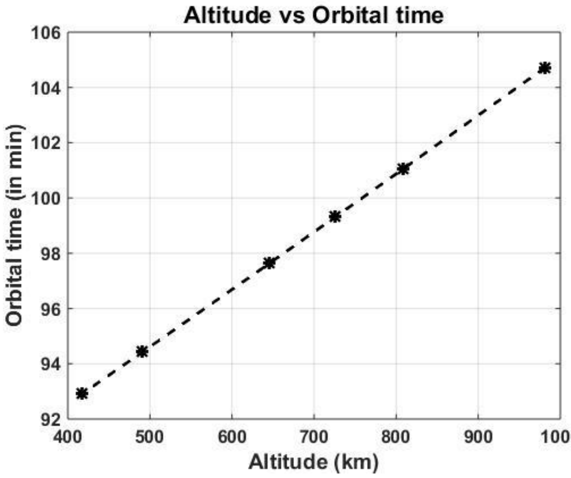

Fig. 1:. Altitude Vs Orbital Time

The fig. 2 provides number of possible orbits available for different repetivity requirements from 400 km to 1000 km. It also indicates the altitudes of those orbits. In can be seen that the number of altitudes to meet the requirement increases with repetivity days.

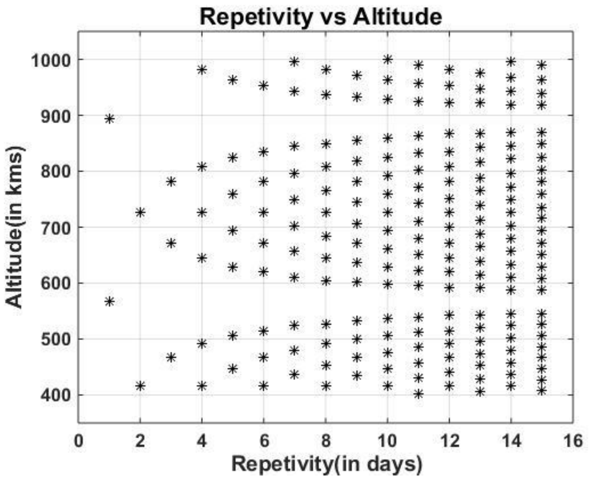

Fig. 2:. Repetivity Vs Altitude

B. Inclination

Inclination is the angle between equatorial plane and the orbital plane at ascending node which defines the orientation of the orbital plane in space. Generally the passive optical remote sensing systems are placed in Sun Synchronous Polar Orbit (SSPO) to image in uniform sun illumination across orbits. The near polar orbit covers areas from South Pole to North Pole. i.e. provides global coverage. SSPO can be defined as the near polar orbit whose normal makes a constant angle with the Sun-Earth vector. Inclination of the SSPO orbit varies with the altitude. Orbits with altitudes from 400 km to 1000 km will have inclinations from 97 to 99 deg. The Sun-Earth direction rotates with an angular velocity (0.986/day) which is equal to the Earth's orbit mean motion (Earth orbit is assumed as circular)

$n_E = 2Pi/T_E \sim 1.991 x 10^{-7}$ rad/s

Where the T_E Orbital time of Earth = 365.25 days.

The sun synchronous can be maintained by rotating the orbital plane w.r.t the Sun-Earth vector. This is possible by utilising the Earth's oblateness effect (J2) that provides required precession of the orbit. The nodal rate can be given as

$$\dot{\Omega} = -\frac{3}{2}\frac{R_E^2}{a^2(1-e^2)^2} n J_2 \cos i \tag{4}$$

Where R_E is Radius of Earth = 6,378 km
a is the orbit semi-major axis
e is the orbit eccentricity,
i is the orbit inclination,
$J_2 = 1.08262 \text{ x } 10^{-3}$ (representing the Earth oblateness effect)

$n=\sqrt{\frac{\mu}{a^3}}$

where µ Earth's gravitational parameter
From above two equations, we get

$$\cos(i) = \cos\left(-4.774 \text{ x } 10^{-15} a^{\frac{7}{2}} (1-e^2)^2\right) \tag{5}$$

The required inclination to maintain the Sun synchronous can be obtained from above equation. The fig. 3 provides the inclination required for different altitudes to be sunsynchronous polar orbit.

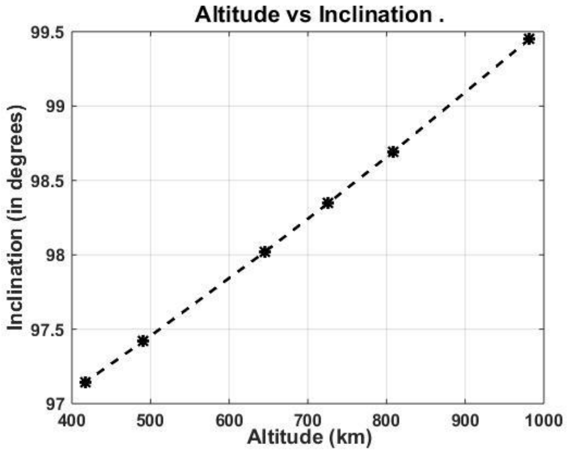

Fig. 3:. Altitude Vs Inclination

C. Equatorial Crossing Time (ECT)

The equatorial crossing time of an SSPO is selected based on amount of radiation required at sensor level and the satellite operation feasibility. Many Earth observation satellites are placed with 10.30 AM ECT orbits. While the optical remote sensing satellites can be operated with a ECT from 9.00 AM to 3.00 PM, microwave remote sensing satellites can be operated with any ECT as they are free from Sun illumination condition on the Earth surface (Target).

ECT around 12.00 noon is not preferred as it causes glints from water bodies. If the Field Of View (FOV) of the sensor is +/- 15 deg, operating the satellite between 11.00 AM to 1.00 PM will cause glints in the image. This is due to the variation of the sun vector w.r.t time. Latitude at which glint occurs shifts based on seasons (Sun vector). If we are forced to operate the satellite with 12.00 noon

ECT, due to ground station availability constraints, small pitch bias on the satellite/sensor is to be provided to avoid the glints for particular latitude.

D. Eccentricity

Eccentricity presents the shape of the orbit. Fig.4 presents ellipse with important parameters

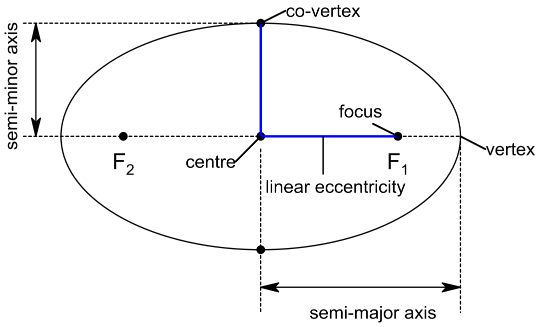

Fig.4: Ellipse and its parameters

The eccentricity of an ellipse can be presented following equation

$$e = \sqrt{1 - \left(\frac{b}{a}\right)^2} \qquad (6)$$

where, e is eccentricity
a is semi-major axis and
b is semi minor axis
e=0 for a circular orbit and 0<e<1 is for elliptical orbits.

If the mission is global, the altitude of the satellite should be same at all locations on the earth, i.e the orbit should to be circular one and the eccentricity should be zero.

III. 3. DERIVING CAMERA SPECIFICATIONS

Deriving camera specifications is an important step in arriving configuration. Desired quality of the image can be obtained with proper specification of the optical system only.

Following camera specification are derived from the resolutions provided by the user.

1. Focal length,
2. Field of View
3. Aperture size
4. Number of pixels
5. Integration time
6. Data rate of Imaging system

A. Focal length

The focal length of an optical system is defined as the distance from the principle plane to the focal plane. Focal length plays an important role in achieving required spatial resolution[8]. Fig. 5 presents the different parameters related to satellite imaging.

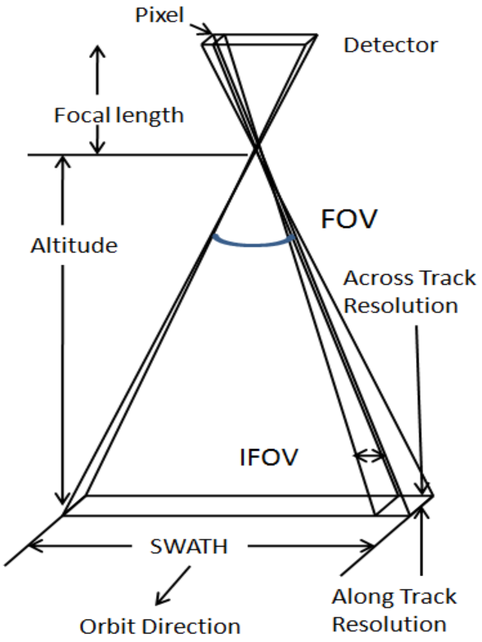

Fig. 5: Imaging configuration

The IGFOV is the projection of the detector on Earth surface. The required focal length of a space based optical imaging system to achieve specified spatial resolution at Nadir view is generally calculated with following formula

$$Focal\ length = \frac{Altitude\ x\ Detector\ size}{Spatial\ resolution} \qquad (7)$$

The smallest possible detector size is dictated by the semiconductor fabrication technology which may be assumed as seven micron at present and the altitude is calculated as explained in previous section. The relation between the spatial resolution and Focal length for different altitudes is presented in fig. 6.

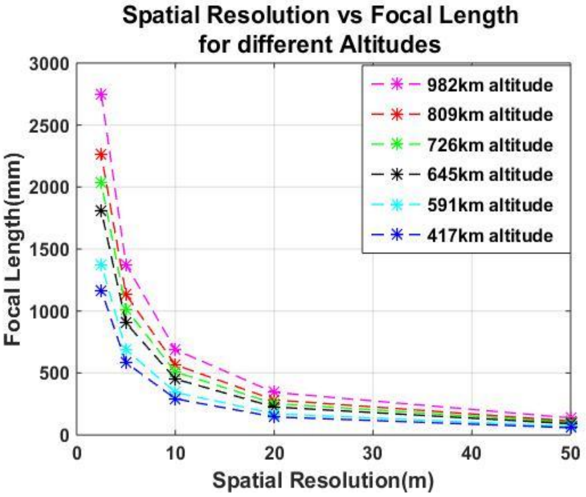

Fig. 6:. Spatial Resolution Vs Focal Length

B. Field of View

The Field Of View (FOV) of an optical system is defined as the maximum angle to which the system is sensitive from the optical axis. Field of view requirement of a space based optical system is calculated with selected altitude and required swath.

The minimum swath required for systematic coverage can be calculated by following formula.

$$Swath(km) = \frac{distance\ between\ successive\ orbits}{repetivity} \qquad (8)$$

Usually the swath will be five to ten percentage more than above calculated value to take care of pointing accuracy error and to get common area for image processing.

The FOV of the imaging system in radian is calculated from the swath and altitude using following equation.

$$Field\ of\ view(rad) = tan^{-1}\left(\frac{swath}{2\ x\ altitude}\right) \qquad (9)$$

In the FOV calculation for wider swath, the curvature of Earth surface is to be accounted.

C. Aperture Size

Aperture size is the diameter of an optical imaging system and it can be expressed as the maximum possible diameter of a light beam that can enter into an optical system. The aperture size controls the amount of radiation available for unit area at image plane. The F/Number is a dimensionless ratio relates the focal length and the aperture size by following formula.

$$F/Number = \frac{Focal\ Length}{Aperture\ Size} \qquad (10)$$

Medium resolution imaging systems with silican based detectors have F-Number value around four.

Sub meter spatial resolution needs focal lengths in tens of meters, but aperture size can't be increased correspondingly. Due to this the F-Number of these systems is high and the signal available at the image plane is less. If focal length doubles with same size, the signal available per unit area in the focal plane decreases to one fourth of original value.

The reduction in the signal due to long focal length may be compensated by increasing the dwell time by reducing the ground trace velocity. This can be achieved by varying the look angle of the sensor in controlled way (staring).

The dwell time can be increased virtually by using Time Delay and Integration (TDI) detectors. The time delay and integration (TDI) mode increases the effective integration time and sensitivity without affecting spatial resolution [9]. Present day high resolution satellites use the TDI technology to improve the Signal to Noise Ratio (SNR).

When the low and medium aperture systems are designed with refractive systems, high aperture systems are achieved by reflective systems. As the reflection is surface phenomenon, reflective systems have advantages of less thickness, feasibility of mass reduction by scooping, and back side mounting.

D. Number of Pixels

Charge Coupled Detectors are used in satellite sensors as they are compact. As the satellite is moving, projection of linear detectors on earth surface moves to image the terrain. The pixels are arranged in line perpendicular to the orbital direction to cover required swath. Number of pixels required to cover selected swath is calculated with swath and spatial resolution using following equation

$$Number\ of\ pixels = \frac{Swath}{Spatial\ resolution} \qquad (11)$$

If required number of pixels is not available in a single detector, multiple detectors are arranged (butted) in the image plane to cover full swath.

E. Integration Time

The integration time is interval between two successive measurements. The integration time usually selected based on the spatial resolution requirement. When the across track resolution is derived from orbital and camera parameters like focal length, altitude and detector size along track resolution is controlled by integration time. As we need square sample, the along track resolution should be equal to across track resolution. . The relation between integration time and spatial resolution for a typical orbit is presented in fig. 7.

The integration time is calculated by following equation

$$Integration\ Time = \frac{Spatial\ resolution}{Ground\ trace\ velocity} \qquad (12)$$

Where, Ground Trace Velocity (GTV) is velocity of the satellite projection on earth

$$GTV = \frac{Orbital\ velocity\ x\ Radius\ of\ Earth}{(Radius\ of\ Earth + Altitude)} \qquad (13)$$

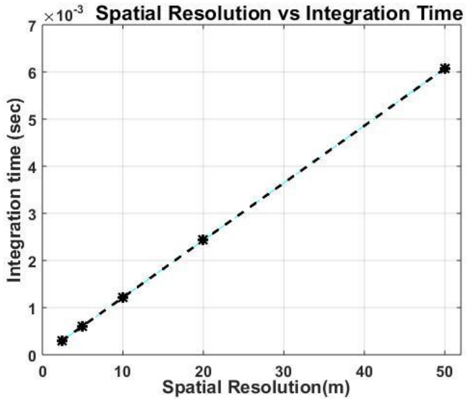

Fig. 7:. Spatial resolution Vs Integration Time

F. Data rate of the imaging system

Though the data rate is not a specification of the imaging system, this feature of the imaging system will be the input for designing data handling system.

Data rate of single band can be computed using following equation

Data rate= P x LPS x Q

Where, P is total number of pixels that covers full swath.
LPS is number of lines collected per sec
Q is number of bits per sample.

Number of lines collected per second is calculated with following equation

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$$\mathit{Lines\ per\ sec} = \frac{\mathit{Ground\ trace\ velocity}}{\mathit{Along\ track\ resolution}} \qquad (14)$$

Or

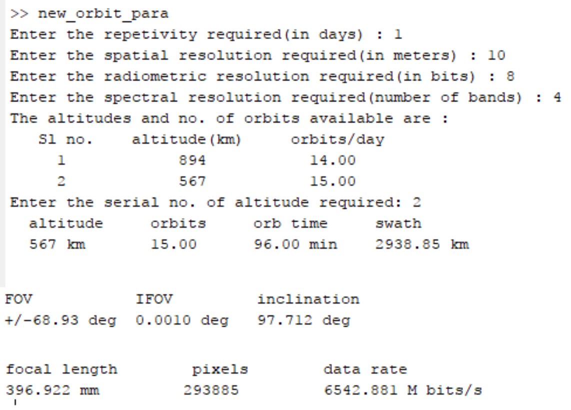
$$\mathit{Lines\ per\ sec} = \frac{1}{\mathit{Integration\ time}} \qquad (15)$$

Here the integration time is assumed equal to sampling interval.
If we use a multispectral imager, then the number of bands is to be multiplied with above value to get final data rate.

IV. RESULTS

(MATLAB Output for different inputs)

Case-1

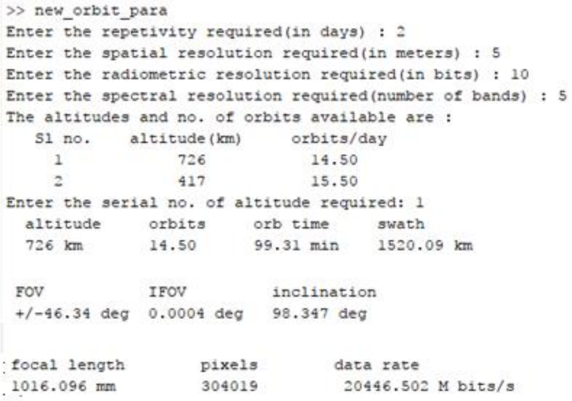


```
>> new_orbit_para
Enter the repetivity required(in days) : 1
Enter the spatial resolution required(in meters) : 10
Enter the radiometric resolution required(in bits) : 8
Enter the spectral resolution required(number of bands) : 4
The altitudes and no. of orbits available are :
   Sl no.    altitude(km)     orbits/day
     1           894            14.00
     2           567            15.00
Enter the serial no. of altitude required: 2
  altitude      orbits      orb time      swath
  567 km        15.00       96.00 min     2938.85 km

FOV           IFOV          inclination
+/-68.93 deg  0.0010 deg    97.712 deg

focal length          pixels        data rate
396.922 mm           293885         6542.881 M bits/s
```

Case-2

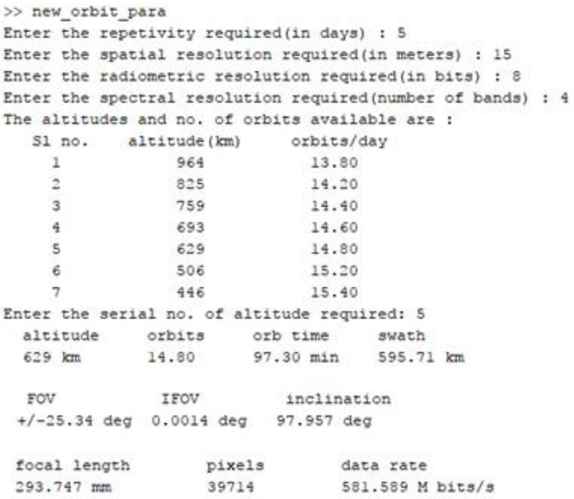


```
>> new_orbit_para
Enter the repetivity required(in days) : 2
Enter the spatial resolution required(in meters) : 5
Enter the radiometric resolution required(in bits) : 10
Enter the spectral resolution required(number of bands) : 5
The altitudes and no. of orbits available are :
   Sl no.    altitude(km)     orbits/day
     1           726            14.50
     2           417            15.50
Enter the serial no. of altitude required: 1
  altitude      orbits      orb time      swath
  726 km        14.50       99.31 min     1520.09 km

 FOV           IFOV          inclination
 +/-46.34 deg  0.0004 deg    98.347 deg

 focal length          pixels        data rate
 1016.096 mm           304019         20446.502 M bits/s
```

Case-3

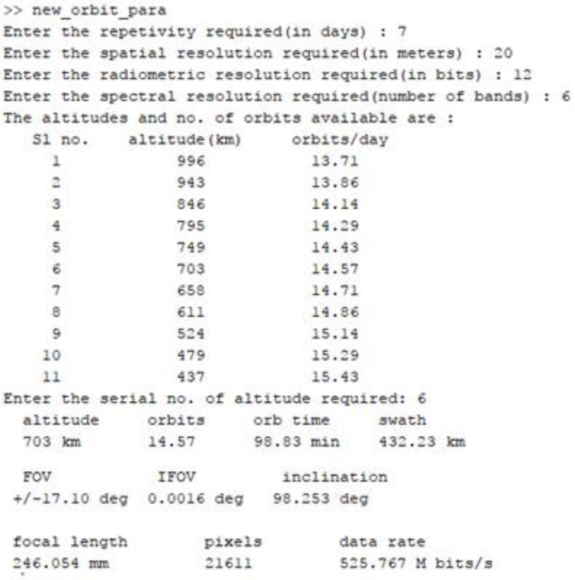


```
>> new_orbit_para
Enter the repetivity required(in days) : 5
Enter the spatial resolution required(in meters) : 15
Enter the radiometric resolution required(in bits) : 8
Enter the spectral resolution required(number of bands) : 4
The altitudes and no. of orbits available are :
   Sl no.    altitude(km)     orbits/day
     1           964            13.80
     2           825            14.20
     3           759            14.40
     4           693            14.60
     5           629            14.80
     6           506            15.20
     7           446            15.40
Enter the serial no. of altitude required: 5
  altitude      orbits      orb time      swath
  629 km        14.80       97.30 min     595.71 km

  FOV           IFOV          inclination
 +/-25.34 deg  0.0014 deg    97.957 deg

 focal length          pixels        data rate
 293.747 mm            39714         581.589 M bits/s
```

Case-4

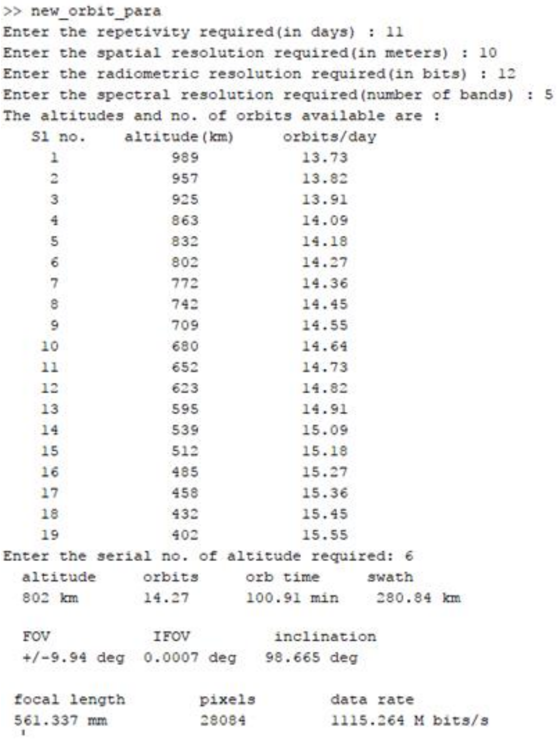


```
>> new_orbit_para
Enter the repetivity required(in days) : 7
Enter the spatial resolution required(in meters) : 20
Enter the radiometric resolution required(in bits) : 12
Enter the spectral resolution required(number of bands) : 6
The altitudes and no. of orbits available are :
   Sl no.    altitude(km)     orbits/day
     1           996            13.71
     2           943            13.86
     3           846            14.14
     4           795            14.29
     5           749            14.43
     6           703            14.57
     7           658            14.71
     8           611            14.86
     9           524            15.14
    10           479            15.29
    11           437            15.43
Enter the serial no. of altitude required: 6
  altitude      orbits      orb time      swath
  703 km        14.57       98.83 min     432.23 km

  FOV           IFOV          inclination
 +/-17.10 deg  0.0016 deg    98.253 deg

 focal length          pixels        data rate
 246.054 mm            21611         525.767 M bits/s
```

Case-5



```
>> new_orbit_para
Enter the repetivity required(in days) : 11
Enter the spatial resolution required(in meters) : 10
Enter the radiometric resolution required(in bits) : 12
Enter the spectral resolution required(number of bands) : 5
The altitudes and no. of orbits available are :
   Sl no.    altitude(km)     orbits/day
     1           989            13.73
     2           957            13.82
     3           925            13.91
     4           863            14.09
     5           832            14.18
     6           802            14.27
     7           772            14.36
     8           742            14.45
     9           709            14.55
    10           680            14.64
    11           652            14.73
    12           623            14.82
    13           595            14.91
    14           539            15.09
    15           512            15.18
    16           485            15.27
    17           458            15.36
    18           432            15.45
    19           402            15.55
Enter the serial no. of altitude required: 6
  altitude      orbits      orb time      swath
  802 km        14.27       100.91 min    280.84 km

  FOV           IFOV          inclination
  +/-9.94 deg  0.0007 deg    98.665 deg

 focal length          pixels        data rate
 561.337 mm            28084         1115.264 M bits/s
```

The results obtained for different requirements are presented in Table-2

V. CONCLUSION

The relation between different orbital parameters and resolutions were studied.

Following studies were carried out in this study:
1. Effect of altitude on the repetivity
2. Focal length Vs Spatial resolution
3. Orbital Time Vs Altitude
4. Focal length with Aperture Size
5. Integration time Vs Spatial resolution
6. Spatial Resolution Vs Data Rate

Table 2 Parameters derived for different requirements

Temporal resolution (Days)	Spatial resolution (Bands)	Spectral resolution (Bands)	Radiometric resolution (Bits/sample	Altitude (Km)	Inclination (Deg)	Orbits/ Day	Orbital time (min)	Swath (km)	FOV (Deg)	Focal length (mm)	Number of Pixels	Data Rate (Mbps)
1	10	4	8	567	97.712	15	96	2938	± 69	397	293885	6542
2	5	5	10	726	98,347	14.5	99.31	1520	±46.3	1016	304019	20446
5	15	4	8	629	97.95	14.8	97.96	595	±25	294	39714	581
7	20	6	12	703	98.253	14.6	98.83	432	±17	246	21611	525.9
11	10	5	12	802	98.665	14.27	100,9	280	±9.9	561	28084	1115

The table shows that the orbital time increases with altitude. It can be noted that many altitudes are suitable for a particular repeativity requirement. The inclination increases with the altitude to maintain sun synchronous. The swath decreases with increase in repetivity days. Increase in altitude reduces the FOV requirement but increase the focal length for selected swath and spatial resolution. From the studies it is noted that the data rate is inversely proportional to square of spatial resolution. As the wide swath and fine resolution increases the data rate, the data transmission capacity restricts the swath and high resolution. Due to this many sub meter resolution missions are focusing on spot imaging rather than systematic coverage. This simple program is useful to the system engineers working in optical remote sensing satellites for the trade-off studies.

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