EROS SYSTEM – SATELLITE ORBIT AND CONSTELLATION DESIGN

Dr. Moshe Bar-Lev, Dr. Leonid Shcherbina, Mr. Vola Levin
Dr. Moshe Bar-Lev, President
ImageSat International N. V. 2 Kaufman Street, Tel-Aviv 61500 Israel. Tel: 972-3-796 0600, Fax: 972-3-516 3430

ABSTRACT

The EROS (Earth Resources Observation System) program conducted by ImageSat International N.V. intends to operate a constellation of 8 commercial imaging satellites in LEO (Low Earth Orbit). The first satellite, *EROS-A1*, was successfully launched by a Russian START-1 launcher on December 5th, 2000, and is presently successfully operating with 1.8 meter to 1.0-meter resolution. This article presents the requirements and considerations regarding the choice of the orbits for a single- and multi-satellite imaging system. The main parameters determining the orbit are: imaging conditions, accessibility and revisit requirements. Two kinds of orbits were compared: Sun-synchronous orbits and inclined orbits. The altitude choice and technique for the Sun-synchronous orbits, providing required ground track repeatability and revisit are analyzed. The final parameters of EROS orbit and constellation are described. Finally, EROS satellites, as well as the proposed services, are presented.

1. INTRODUCTION

The world commercial services for space high-resolution imagery market faced fast growth during the last few years. Russia made available her archives of high-resolution imagery, and the American authorities legislated lenient regulations, allowing the commercial marketing of space imagery with resolution of 1 meter and lately 0.5 meter. As a result, several attempts were made by different companies to provide services of high-resolution satellite images. Space Imaging Inc. successfully launched *IKONOS-2* few months after a failure in launching of *IKONOS-1* (1999). EarthWatch Inc. has failed in both its launch attempts of *EarlyBird* (1997) and *QuickBird* (2000) and is planning to launch this year. ImageSat International's *EROS-A1* was successfully launched in December 2000 and became the second company to provide high-resolution commercial services. The company intends to deploy a constellation of 8 satellites with imaging resolution, better than 1 m, in the next 6 years.

Satellite orbit is determined by mission requirements and may sometimes be limited by launch restrictions. The imaging mission design goal is <u>to achieve the largest amount of imagery with the best quality and the best coverage of areas for a longest time</u>. Compromises of these requirements determine the satellite orbit. The imaging quality is composed of the resolution and swath width, as well as the illumination conditions. The area covered is defined by either as a requirement for global worldwide coverage or a requirement for frequent revisit of limited specific regions. The best coverage is achieved by maximizing the frequency of imaging revisit, imaging velocity and the maximum swath.

A constellation of imaging satellites shall increase the amount of imagery and the coverage. The constellation design criteria must take into account the proper phasing of the satellites, provision for redundancies and the operational restrictions of the controlling ground station and imagery receiving stations.

The orbit and constellation considerations for the electro-optical imaging satellites, operating in the visual band are presented. For other kinds of imaging satellites, such as radar based or infrared, some of the considerations may differ somewhat. Most of the principles presented, are generally relevant to all kinds of imaging satellites

Chapter 2 below presents the mission for imaging orbits. Obit design for a single satellite is presented in Chapter 3 and considerations, regarding satellites constellation, are discussed in Chapter 4.

The EROS system is presented in Chapter 5.

2. MISSION REQUIREMENTS FOR IMAGING SATELLITES

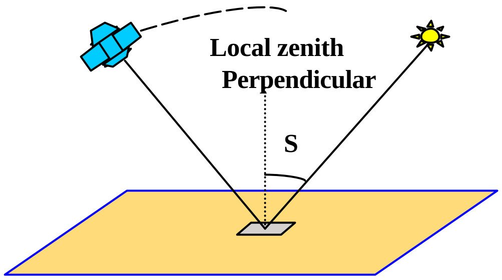
2.1. Orbit Requirements

2.1.1. Imaging Quality

Illumination Conditions

The required illumination conditions is a major factor in achieving high imaging quality since the energy collected by the imaging camera in the visual band is the light reflected from the targeted area,

The Sun Angle, i.e. the angle between the local perpendicular and the Sun direction, See Figure 1, defines the illumination condition of a specific area. The existing satellite cameras provide satisfactory images at *Sun Angles* up to $60° \div 80°$.



The best illumination is achieved at minimal *Sun Angles*, i.e. Sun in local zenith, but this will not necessary lead to the best quality of accepted images, especially for high-resolution imaging. For better interpretation and distinction between different images details, some shadow is useful. Therefore, it is recommended to perform imaging for *Sun Angles* of about 20° ÷ 40°.

Figure 1. Sun Angle Definition

Weather conditions such as haze, fog and clouds are a very serious obstacle in Earth imaging. Some areas, especially those close to the equator or to oceans, are known for their high cloudiness. Generally, the cloud coverage level is seasonal and has a daytime dependence nature.

Inclined orbits, for electro-optical satellites, leads to varying illumination conditions for each pass, as well as to gaps of several weeks in imaging possibility (night passes only).

The use of Sun-synchronous orbit for imaging satellite, as shall be presented in par. 2.3 below, allows almost the same illumination conditions for every imaging pass. The local time of the ascending/descending nodes is then defined by required shadows/cloudiness conditions

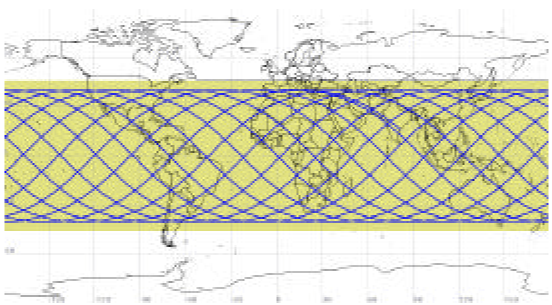
2.1.2. Imaging Resolution and Swath Width

The resolution requirement for a given observation system is determined by the orbit altitude. The lower the orbit, the better the imaging resolution, however, the smaller the swath width and the shorter the satellite lifespan are.

2.2. Coverage Requirements

The coverage requirements are: Accessible area coverage, coverage zone of receiving ground station, ground track repeatability and revisit period.

The Accessible area coverage is defined as the Earth area, which may be covered by the satellite.



Actually, the Physical coverage area of the satellite lies between the north and south meridians with latitude equal to the orbit inclination angle (see Figure 2). The satellite may perform off-nadir imaging by pointing its camera at an angle g to the nadir, see Figure 3. Therefore, the actual possible coverage area is determined by the orbit inclination and the maximal imaging pointing angle of the camera. A polar orbit shall allow a global worldwide coverage.

Figure 2. Earth Coverage Area for Inclined Orbit of 40°

The coverage zone of a receiving ground station is limited geometrically by the Line of Sight between the Ground Antenna and the satellite, determined by the orbit altitude H, as well as by technical parameters, like communication link between the station and the satellite, minimal antenna elevation over the local horizon a and maximal off-nadir imaging angle – see Figure 3.

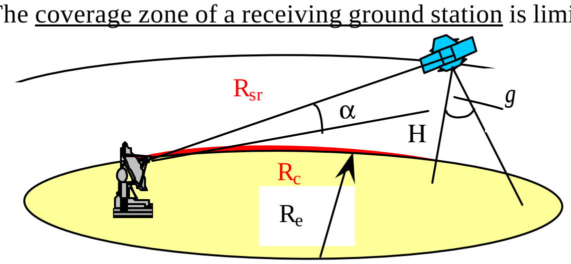


Figure 3. Ground Station Coverage Zone

The coverage zone radius R_c is given by the following expression:

$$R_c = R_e \cdot \left[\arcsin\left(\frac{R_{sr}}{R_e + H} \cdot \cos a\right) + \arcsin\left(\frac{R_e + H}{R_e} \cdot \sin g\right) - g \right] \quad (1)$$

where: R_e - Earth radius, R_{sr} - Slant range radius:

$$R_{sr} = R_e \cdot \left(-\sin a + \sqrt{\sin^2 a + 2 \cdot \frac{H}{R_e} + \left(\frac{H}{R_e}\right)^2} \right) \quad (2)$$

The higher the orbit the bigger the coverage zone. For satellite systems, having no onboard recording, the coverage area will consist of the coverage zones of the ground stations.

The ground track repeatability is defined by the time period (in days) between the satellite revolutions having the same ground track. This parameter is important for imaging mission prediction and planning. Some systems, like *SPOT*, require the exact repeatability of the ground track for long term. This can be achieved by having relatively high orbits (above 600 km), which are weakly disturbed. For lower orbits, the ground track repeatability can be maintained for only short terms only because of the higher drag effect on the change on the orbit height.

The revisit period is defined for a specific site and represents the minimal time interval (in days) between two imaging opportunities of this specific site. The longest revisit period is for equator located sites. The revisit shortens, as the site location is located at higher latitude. It should be also mentioned, that the lower the orbit inclination, the better (shorter) the revisit period. This is a major disadvantage of the polar orbits.

2.3. Orbit Definition

The satellite orbit can be defined by the classical set of Keplerian parameters [1], referred to the *vernal equinox* inertial coordinate axes, see Figure 4:

a) a - semi-major axis
b) e - eccentricity
c) i - inclination angle
d) W - right ascension of ascending node
e) w - argument of perigee
f) q - true anomaly

$$a = \frac{r_a + r_p}{2} = R_e + \left(\frac{H_a + H_p}{2} \right) \quad (3)$$

$$e = \frac{r_a - r_p}{r_a + r_p} = \frac{H_a - H_p}{2 \cdot R_e + H_a + H_p} \quad (4)$$

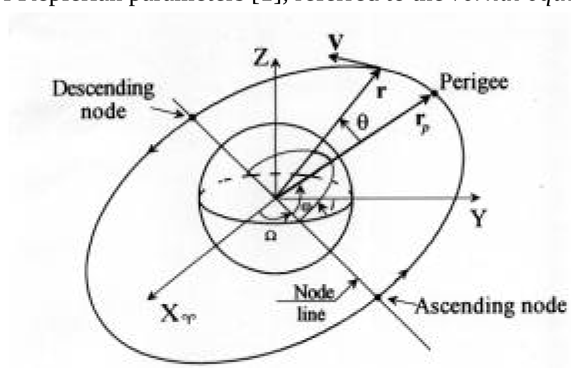


Figure 4. Orbit Definition Parameters

Motion of Orbital Pane

Because of the nonhomogeneity and oblateness of the Earth, the orbital plane doesn't remain inertialy fixed, but suffers two main motions:

a) orbital plane rotation around the North-South axis, characterized by the following expression:

$$\dot{\Omega} \cong -9.97 \cdot \left(\frac{R_e}{a} \right)^{3.5} \cdot \left(1 - e^2\right)^{-2} \cdot \cos i \qquad \text{[deg/day]} \qquad (5)$$

b) in-plane rotation of the orbital ellipsoid, given by:

$$\dot{w} \cong 4.98 \cdot \left(\frac{R_e}{a} \right)^{3.5} \cdot \left(1 - e^2\right)^{-2} \cdot \left(5 \cdot \cos^2 i - 1\right) \quad \text{[deg/day]} \qquad (6)$$

These phenomena allow some special kinds of orbits:

a) Sun-synchronous orbit, characterized by synchronizing the rate of change of ascending node ascension to the rate of the Earth rotation around the Sun, i.e.: $\dot{\Omega} = 360°/\,year = 0.9856°/\,day$ (7)

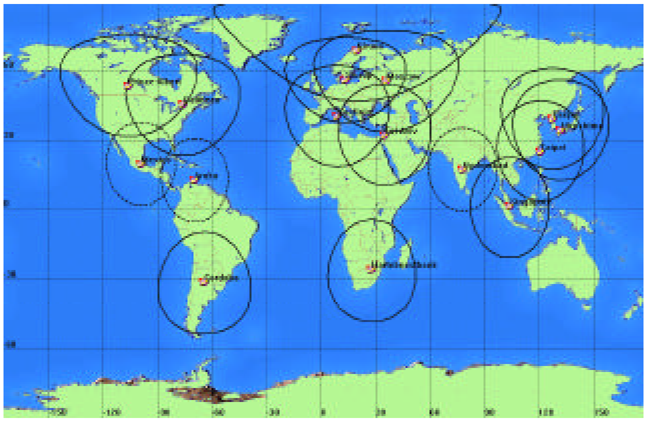
For LEO orbits, (5) and (7) lead to the orbital inclination within i ~ 96° ÷ 98° range, i.e. almost polar orbits. In this orbits the revisit time at any point is at the same time of the day.

b) Frozen orbit, i.e. the orbit with constant argument of perigee, is derived from (6) by setting $\dot{w} = 0$, which leads to orbit inclination of $i = 63.43°$. This orbit is also known as *Molniya-type orbit*, since it was used for the first time by Russian Molniya-type communication satellites, where the orbit high apogee was constantly located over the north hemisphere, leading to long duration of communication time for the specific satellite over the northern part of Russia.

3. ORBIT DESIGN FOR *EROS-A1* SATELLITE

3.1 Orbital Plane Orientation

EROS mission requires provision of the Earth imaging within 2,000 km radius coverage zones of ground receiving stations, located all over the world. The location of existing ground receiving stations is presented in Figure 5.



A circular orbit close to polar is required to fulfill the above coverage requirements.

In order to provide the best illumination conditions during all satellite passes, as required for the global coverage, a Sun-synchronous orbit, which is close to polar, was chosen. The chosen local time of descending node was 09:45 a.m., in order to minimize clouds presence for the Far-East region.

Figure 5. Worldwide Network of Existing EROS Ground Receiving Stations

3.2 Orbit Altitude

Preliminary the orbit altitude range of 460 ÷ 500 km was derived from the imaging resolution/swath and the lifetime requirements. The exact value of the satellite orbit was chosen to provide best ground track repeatability and revisit.

The ground track repeatability and revisit calculation is based calculating the synchronization between the motions of the Earth and the satellite.

Ground track repeatability will be achieved, if during an integer number of days *M* the satellite has an integer number of revolutions *N*. For the Sun-synchronous orbit, the revolution period P of such orbit is given by the following expression:

$$P = T_{sn} \cdot M / N \qquad (8)$$

where: T_{sn} - solar day; $T_{sn} = 86{,}400\,\text{sec}$

Such an orbit will have the ground track repeatability with a period of *M* days. *N* can accept any integer value within the range:

$$N = M \cdot L_{\min} \div M \cdot (L_{\min} + 1) \qquad (9)$$

where: L_{min} - minimal integer number of revolutions per day; for the orbit altitude range of 275 ÷ 576 km: L_{min} = 15

The equatorial distance *D* between two successive passes is given by the following:

$$D = R_e \cdot w_e \cdot P \qquad (10)$$

where: w_e - Earth rotation rate; $w_e = 2p / T_{sd}$, T_{sd} - sidereal (inertial or star) day

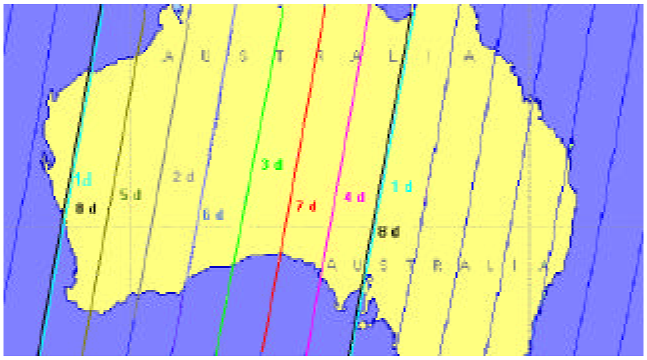
The value of *N* shall be chosen such as to provide best revisit of any site located on equator (worst case), i.e. best coverage of the distance *D* during *M* days.

For *EROS-A1* satellite, a 7 days ground track repeatability was chosen. The parameters of the possible orbits, depending on the value of *N*, are presented in Table 1. *dD* represents the daily movement of the ground track crossing point at the equator:

$$dD = (L_{\min} + 1) \cdot D - 2pR_e \qquad (11)$$

Table 1. Earth Synchronized Orbits with 7 days Ground Track Repeatability

	M days =	7						
N	*L*	*P*, sec	*a*, km	*H*, km	*D*, km	*dD*, km	*dD/D*	*dD/D* * *M*
105	15.00	5,760.0	6,945.0	566.9	2,671.7	2,671.7	1.00	7
106	15.14	5,705.7	6,901.3	523.1	2,646.5	2,268.4	0.86	6
107	**15.29**	**5,652.3**	**6,858.2**	**4 80.1**	**2,621.7**	**1,872.7**	**0.71**	**5**
108	15.43	5,600.0	6,815.8	437.7	2,597.5	1,484.3	0.57	4
109	15.57	5,548.6	6,774.1	395.9	2,573.6	1,103.0	0.43	3
110	15.71	5,498.2	6,732.9	354.8	2,550.2	728.6	0.29	2
111	15.86	5,448.6	6,692.4	314.3	2,527.3	361.0	0.14	1
112	16.00	5,400.0	6,652.6	274.4	2,504.7	0.0	0.00	0



The orbit, corresponding to N =107, was chosen, with the equatorial distance between two successive passes D = 2,622 km and daily move of the equator cross of dD = 5/7 D (or equivalently 2/7 D). The 7 days ground track map is shown in Figure 6. The gap between the two neighbor equatorial crosses is 375 km, which can be covered for the worst-case revisit period of days by off-nadir imaging with imaging angles up to 21°. The use of higher imaging angles or/and for sites' locations with higher latitude meaningfully improves (reduces) the revisit period.

Figure 6. Map of 7 Days Passes for 480 km Sun Synchronized Orbit

For example, for imaging angles up to 37° the revisit period of 3÷4 days can be provided even for equatorial sites. The same revisit period can be achieved for all sites, located to north / south of ±41° latitude, with imaging angles up to 30°.

4. ORBITAL CONSTELLATION DESIGN

A constellation of satellites has the following benefits:

a) Increase the amount of imagery received.

b) Allows daily revisit for any point with highest with minimal imaging angle. As shown in par. 3.2, one satellite in the EROS constellation has a 7 days revisit period at low imaging angles at the equatorial area (worst case). Use of a constellation of 7 satellites, properly phased will lead to a daily revisit of any site all over the world at the almost highest resolution. The EROS system plans to use an 8 satellites constellation, out of which one spare satellite.

c) Achieve imaging opportunities for areas, with high cloudiness, by allowing imaging opportunities during clear or partially clear hours. This requires distributing the satellites orbits into different orbital planes with a wide range of local times of the descending nodes, varying from morning hours till afternoon. The 8 satellites constellation will be placed into 8 separate Sun-synchronous orbital planes with the following local times: 9:45 a.m., 10:00 a.m., 10:30 a.m., 11:00 a.m., 1:00 p.m., 1:30 p.m., 2:00 p.m., 2:15 p.m. EROS constellation orbital planes are presented in Figure 7.

d) Operational constraints of the ground stations shall be taken into account: a minimal time interval of 10 min. is required between any two successive satellite appearance at the communication range of each ground station. Since a single satellite pass within the communication range of a ground station lasts up to 10 min., the minimal phasing of 20 min. (75°) between any 2 satellites in 2 neighbor planes is required, see Figure 8.

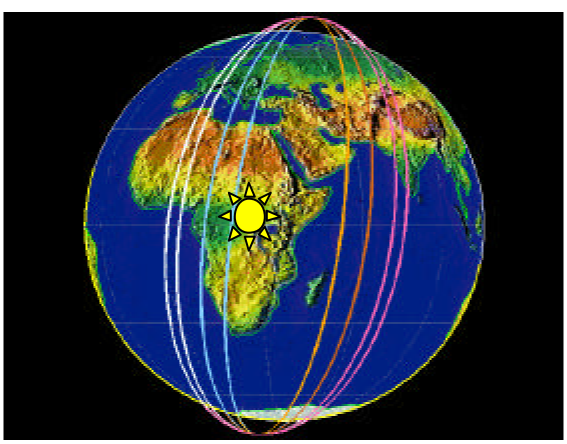


Figure 7. Orbital Planes of EROS Constellation

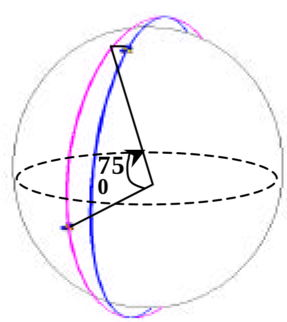


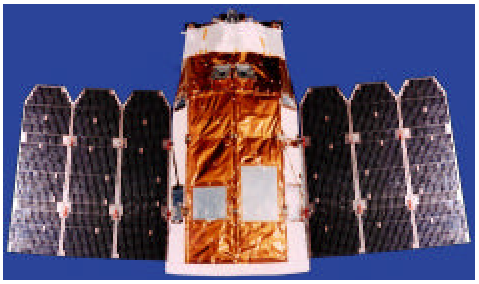
Figure 8. 75° Phasing between Two Satellites in Neighbor Planes

5. EROS PROGRAM

5.1 General

The EROS program aimed to supply commercial high-resolution images and services using a constellation of Sun-synchronous satellites launched and operated by ImageSat.

5.2 EROS Satellites



EROS-A1 satellite (see Figure 9), the first satellite of the constellation, was successfully launched on December 5, 2000 from the Russian Cosmodrome Svobodny, located in southeast Siberia. The satellite has passed the IOT (In-Orbit Tests) program and is in commercially operational. The second satellite, *EROS-B1*, is planned to be launched in 2003

Figure 9. EROS-A1 Satellite

The main parameters of *EROS-A1* and *EROS-B1* satellites are presented in Table 2.

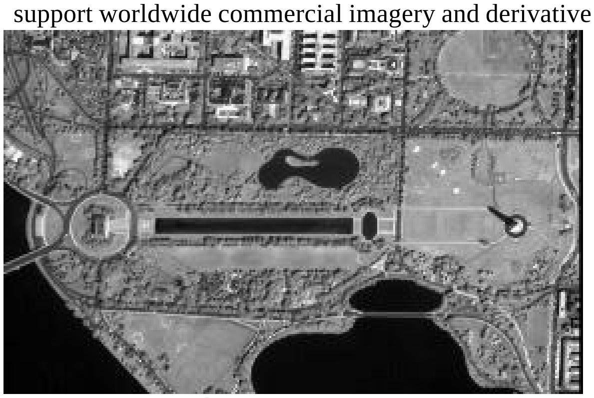
Table 2. Main Operational Parameters of *EROS-A1* and *EROS-B1* Satellites

Parameter	*EROS-A1*	*EROS-B1*
Weight	250 kg	350 kg
Dimensions (Launch)	∅1,210 * 2,235 mm	∅1,210 * 2,255 mm
Orbit Altitude	480 km	600 km
Lifetime	Over 6 years	Over 10 years
Imaging Sensor	CCD Line,> 7,000 pixels	CCD TDI, 32 stages, > 15,000 pixels
Panchromatic Imaging Resolution (GSD) at Nadir Swath Sampling Depth	 1.8 m 12 km 11 bits	 0.87 m (@ 600 km) 13 km 10 bits
Multispectral Imaging Resolution (GSD) at Nadir Swath	None	4 bands 3.5 m 13 km
Video Transmission Rate	70 Mbit/sec.	280 Mbit/sec.

5.3 EROS Services

EROS system proposes the following services:

- Satellite Operating Partner (SOP) Programs: provide the customer with exclusivity for full planning and tasking and acquisition ability within the footprint of the customer's ground station.
- Acquisition, Archiving and Distribution (AAD) Programs:. Existing ground stations, (see figure 5) adapted for reception of EROS images, supports this service. The imaging tasking is performed by EROS central ground station. The ground stations participate in satellite imagery reception, archiving and distribution operations to support worldwide commercial imagery and derivative product sales.



Washington D.C

Paris

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[2] James R. Wertz & Wiley J. Larson "Space mission analysis and design", Third Edition, Space Technology Library 1999