Moonsat: An Orbital Imaging System for Mapping the Moon

Donald L. Light

Abstract

On 20 July 1989, two decades after the first Apollo landing on the Moon, President George Bush proposed a long-range, continuing commitment that called for revisiting the Moon to establish way-points for the long-range plan to land on Mars. Accepting this challenge, NASA then established the Space Exploration Initiative which plans to include a polar orbiting lunar imager to map the Moon. Moonsat is proposed as such a lunar imaging system. Spatial and spectral resolution requirements as proposed enable Moonsat to support mapping of the lunar topography and to determine the composition of soils and rocks for mineralogy and natural resource assessment. Moonsat's design calls for sensing high resolution pixels in the panchromatic band from in-orbit stereo. The position and attitude of Moonsat will be taken from Earth-based tracking and, if feasible, the Global Positioning System when Moonsat is on the visible side, and attitude will be taken from star sensors time-synchronized with the ground-looking linear array sensors. Moonsat's orbital altitude (100 km), period (118 min), spatial resolution (4 m), and swath width (35 km) will provide full contiguous coverage of the Moon's surface. These data can be used for a variety of applications to support the Nation's Space Exploration Initiative.

Introduction

The lunar exploration satellites Ranger, Surveyor, and Lunar Orbiter all paved the way for Apollo's mission to the Moon (Light, 1970). But, it was the highly successful Apollo Program that captured the eyes and ears of the world on 20 July 1969, when Apollo 11 Astronaut Neil Armstrong made his "giant step" for mankind onto the surface of the Moon. Soon to follow were the remaining Apollo's 12, 13, and 14 for continued exploration, although Apollo 13 had to turn back before completing its mission. Then the final three Apollo's 15, 16, and 17 orbited a mapping system designed for mapping the Moon. This system contained a frame camera (3-inch focal length) integrated with a star camera for attitude sensing, and a panoramic camera (24-inch focal length) for high resolution photography of the landing sites (Light, 1972; Light, 1980; Doyle, 1970).

These two Apollo cameras collected miles of valuable film from the Lunar landscape, but unfortunately the Apollo missions were in near-equatorial orbits designed to land man at the chosen landing sites (NASA, 1973). The six landing sites are between 10° south latitude to 27° north latitude. But, the 12 men who trod the lunar surface in the course of six Apollo missions could not venture more than five miles from their landed spacecraft. As a result of the restricted geographic scope of these missions, the astronauts could do little more than scratch the surface in exploring the Moon. So, the total surface of the Moon outside the Apollo sites has not yet been sufficiently photographed.

New Space Exploration Goals

It has been 20 years since Apollo 17 (11 December 1972) landed on the Moon, and soon thereafter active lunar exploration came to a close. After years without exploration activity, the Report of The National Commission on Space (NCOS), *Pioneering the Space Frontier* (Paine, 1986), formulated an aggressive civilian space agenda to carry America into the 21st Century. NCOS recommended that the first lunar outpost be established within the next 20 years, and permanently occupied lunar bases, within the following decade. The report noted that, as revisits to the Moon become more frequent, the need will grow for larger base camps to serve as supply centers, outposts, etc. In July 1989 President Bush challenged America: "... back to the Moon, back to the future. And this time, back to stay. And ... a journey into tomorrow ... a manned mission to Mars" (Stafford, 1991; Asker, 1992). The long-range goal is to land astronauts on the planet Mars by using the Moon as a way-point or outpost to support the development of the space frontier. Outposts will permit the extension of lunar exploration for the purpose of both scientific and resource development. NASA's Space Exploration Initiative should concentrate on a step-by-step program for establishing a lunar outpost. Adequate maps should be made before establishing such an outpost. To handle the program, NASA's Space Exploration Office is developing a 10-year plan for planetary cartography that addresses the total program. Although the plan is not yet final, it is known to support Lunar Scout Missions that would be polar orbiting resource mappers collecting image data to support lunar exploration. Plans may call for a scout launch in 1996, and a second launch in 1998. A leading sensor candidate is the High Resolution Stereo Camera being built for the Mars 94 mission under the auspices of the Federal Republic of Germany's DLR (Neukum, 1990; Neukum, 1992). To date, Congress has not funded the program, so plans are not specific at this time. In any case, a near-polar orbiting satellite to photograph the way for future explorations should be part of the plan. In recognition of the need for a polar orbiting imager, the remainder of this paper develops the concept called "Moonsat: An Orbital Imaging System for Mapping The Moon." The

---

U.S. Geological Survey, 511 National Center, Reston, VA 22092.

Photogrammetric Engineering & Remote Sensing,
Vol. 60, No. 12, December 1994, pp. 1421–1429.

0099-1112/94/6012-1421$3.00/0
© 1994 American Society for Photogrammetry
and Remote Sensing

TABLE 1. RECOMMENDED MAP SCALE AND GROUND RESOLUTION (RG)

Map Scale	Rg m/pixel	Use
1:5,000,000	1,000	Global
1: 250,000	50	Regional
1: 50,000	4-10	Science
1: 5,000	1	Landing sites

Moonsat Concept is suggested as a candidate for NASA's Space Exploration Initiative this decade.

Requirements for Moonsat

During the pre-Apollo years, NASA convened two conferences for lunar scientists interested in lunar exploration. The first was convened in Falmouth, Massachusetts, 19–31 July 1965. The second such conference was convened at Santa Cruz, California, 31 July to 13 August 1967, to update, as necessary, the findings of the Falmouth conference. Both conferences contained Geodesy and Cartography Working Groups whose reports document a set of scientific objectives in this area.

At these conferences the Geology and Geophysics Working Groups proposed requirements for cartographic support of their own programs. Generally, this cartographic support was implied rather than stated explicitly, but the essential steps in the development of geodetic/cartographic knowledge of the Moon were developed.

- Establish a selenodetic coordinate system related unambiguously to the right ascension-declination system.
- Describe, in sufficient detail, the gravitational field of the Moon.
- Derive a reference figure with respect to a point which is representative of the Moon's center of mass.
- Establish a three-dimensional geodetic control network over the lunar surface in terms of latitude, longitude, and height above the chosen reference figure.

The Geology Working Groups at both conferences agreed upon the need for maps at scales as small as 1:5,000,000 for covering the whole Moon and large-scale maps at 1: 1,000,000, 1:250,000, 1:50,000, and as large as 1:5,000 for specific sites. NASA's current Planetary Cartography Working Group (Doyle, 1992) has suggested only four map scales, as shown in Table 1. The typical ground resolution (Rg) per pixel that is sufficient for each scale is also given. The manager of the Lunar Scout Program at NASA's Johnson Space Center has suggested a 4-metre pixel size (M.G. Conley, personal communication, 1992).

Given these geodetic and cartographic objectives, it is essential that a Lunar orbital imaging system be designed to produce a remote sensing database that meets the essential needs of the Space Exploration Initiative (M.D. Griffin, personal communication, 1991). The majority of these needs can be satisfied with a system such as Moonsat that can collect data to produce the following products:

- High-spatial-resolution panchromatic imagery in stereo for compiling
  - —image maps,
  - —digital elevation models (DEMs),
  - —topographic maps, and
  - —control point network;
- Multispectral imagery for
  - —mineralogy, soil composition, and rock types; and
  - —searching for traces of water ice near the poles.

Moonsat's design characteristics are somewhat similar to the Earth sensing systems previously proposed by Colvocoresses (1982) and Light (1990).

Scale and Resolution: Spatial and Spectral

In a recent book about geographic information systems, Star and Estes (1990), emphasized the four Ms, (measure, map, monitor, and model) as essentials for improving our understanding of the world around us. The following Moonsat concept is designed to permit the four Ms. Even though all data are not scale related, most are, and therefore it is useful to establish a scale relationship among the data. Establishing a product scale, even for lunar maps, sets up a basis for quantifying the accuracy requirements for sensor measurements that would be taken by Moonsat. Because the image map, contours, and digital elevation model (DEM) comprise a complete description of the Moon's surface, specifications for image maps, contour intervals, and DEMs can be used to establish Moonsat's system design characteristics.

To support scientific study, the Planetary Cartography Working Group suggested 1:50,000-scale topographic products. Smaller scale products can be made from the 1:50,000-scale images acquired by Moonsat. The 1:5,000-scale product falls outside of Moonsat's design characteristics. Be it graphic or on digital media, the topographic product can be thought of as providing three basic kinds of information: (1) content, (2) location, and (3) elevation. Then the U.S. National Map Accuracy Standards (NMAS) can serve as a basis for sensor system requirements for content (ground spatial resolution), location (spatial position), and elevation (stereo measurement for elevations, contours, or digital elevation model data). Based on the NMAS, the standard error of location coordinates may not exceed

$$\sigma_L \text{ (m)} = 0.3 \times 10^{-3} \times \text{(map scale number)}, \quad (1)$$

and the standard error of elevations should not exceed

$$\sigma_h \text{ (m)} = 0.3 \times \text{(contour interval)} \quad (2)$$

Table 2 shows the NMAS and typical contour intervals for four map scales.

Table 2 establishes the 1:50,000-scale accuracy criteria for location and elevations. Because spatial resolution requirements for ground pixel size can be related to elevation accuracy and contour intervals, the pixel size is set by the required contour interval. Using this technique, the required contour interval of the final product can be used to establish the geometric characteristics of the Moonsat mission.

Determining Pixel Size for Spatial Resolution

Two different methods, one using a printing criterion and one using a photogrammetric criterion, have been developed (Light, 1990) to determine the appropriate pixel size of the sensor footprint on the ground. The printing criterion as-

TABLE 2. NMAS REQUIREMENTS FOR LOCATION AND TYPICAL CONTOUR INTERVALS

		Contour Interval (CI) = 3.3 σ_h Typical contour interval (m)						
Map Scale	Location σ_L (m)	5	10	20	30	40	50	100
250,000	75	—	10	20	—	40	—	100
100,000	30	—	10	20	—	—	50	—
50,000	15	—	10	20	—	40	—	—
25,000	7.5	5	10	20	—	—	—	—

*1:50,000 scale requires $\sigma_h = \pm 3$ m for the smallest CI of 10 m.

TABLE 3. MOONSAT SENSOR SPECTRAL CHARACTERISTICS WITH APPLICATIONS AND SPATIAL RESOLUTION

Spectral region	Band width (μm) or centers	Application	Spatial resolution (m)
1. Panchromatic	0.40–0.80	Crater density, morphology, topo mapping, and DEMs	4
2. Blue	0.40	Ti and Fe content, soil maturity	10
3. Green	0.56	Distinguish highland rocks versus basalts	10
4. Red	0.70	Ferric iron detection	10
5. Near infrared	0.95	Ferrous iron absorption in olivine and pyroxene	10
6. Near infrared	1.20	Ferrous iron absorption shoulder	10

sumes that the typical 150-line/inch lithographic printing screen (actually 300 lines/inch) can transfer all the information that can be used at normal viewing distance by the human eye when observing quality image printing. The relationship between ground pixel size (m/pixel) and image scale (Is) is given by the following:

$$\text{Pixel size (Ps)} = \frac{1 \text{ inch}}{300 \text{ lines}} \times \frac{1 \text{ m}}{39.37 \text{ inch}} \times \text{Is}$$

$$\text{Ps} = 8.47 \times 10^{-5} \times \text{Is} \tag{3}$$

Example: for Is = 50,000,

$$\text{Ps} = 4.2\text{m/pixel}.$$

The second method (Light, 1990) uses the well-known parallax equation from photogrammetry as the criterion to determine the pixel size needed (see Table 2) to compute elevations accurate to meet $\sigma_h = 3$ m, which supports a 10-m contour interval (CI).

The equation using the photogrammetric criterion is

$$\text{Ps} = \frac{1}{K} \times \frac{B}{H} \times \sigma_h \tag{4}$$

where

K is a nondimensional number expressing the degree to which correlation can be achieved with a stereoimage (for example, $K = 0.50$ means a correlation error of about one-half pixel);

B is the base distance between sensor positions when the stereo pixels are detected ($0.6 \leq B/H \leq 0.9$ is typical for space systems);

H is the orbital height of the sensor above the mean radius of the Moon;

σ_h =0.3 x CI as stated in the NMAS;
(Example: assume $B/H = 0.7$ and CI = 10 m as given in Table 2);

$$\text{Ps} = \frac{1}{0.50} \times 0.7 \times 0.3 \times 10 \text{ m; and}$$

$$\text{Ps} = 4.2 \text{ m.}$$

Recognizing that both methods yield the same 4.2-m pixel size, it can be concluded that imagery with a 4-m spatial resolution will provide 1:50,000-scale topographic products, including DEMs and image maps for a wide variety of lunar GIS applications.

Spectral Sensing and Resolution

Several insightful articles published by lunar scientists (Nash and Conel, 1974; Charette *et al.*, 1974; Soderblom and Boyce, 1976; Head *et al.*, 1978) generally concerned themselves with characterization of lunar surface units using remote observations from different wavelengths. These articles form the basis for the multispectral wavelengths suggested for Moonsat.

Electromagnetic and particle radiation are the only sources of information available to the remote observer of the lunar surface. Sunlight is either passively reflected or absorbed by the lunar surface. Absorbed radiation is converted to heat and re-emitted as thermal radiation. Solar radiation in the spectral region of 0.3 to 2.5 μm reflected from rocks and soils has two major components: (1) specular (first-surface) reflectance, and (2) diffuse scattering. Only a few portions of this part of the electromagnetic spectrum have been measured and shown to be useful and/or practical for remote observations of planetary surfaces. Because of this, the spectral bands suggested for Moonsat are selected within the 0.3- to 2.5-μm region. Basically, multispectral sensing on the Moon is to support mapping the topography (0.40 to 0.80 μm) and scientific investigations of the properties of surface materials. As shown in Table 3, conclusions can be drawn as to the composition of the surface materials of the Moon, specifically, iron (Fe) and titanium (Ti) content.

Overall, the multispectral capability suggested for Moonsat should permit

- investigation of surface features and determination of their morphology and structural and/or magmatic causes;
- determination of the chemical and mineralogical composition and physical state of solid surfaces; and
- geoscientific interpretation and thematic mapping.

Table 3 lists the suggested spectral bands for Moonsat.

The Moon's Orbital Characteristics

The Moon's period of revolution around the Earth is exactly equal to its period of rotation on its axis, so it always keeps the same face turned toward Earth. The Moon requires 27.32 days (sidereal month) to make a complete 360° rotation of the Earth and return to the same place relative to the stars. During that time, the Earth is revolving around the sun at about 1° per day (360°/365.25 days). With reference to the sun, the Moon takes 29.53 days (synodic month) to go from full Moon to full Moon or to complete one full lunar cycle. The synodic month is the time basis for Moonsat's orbits. The Moon rotates very slowly compared to the Earth's rotation. The rate of rotation is 0.549°/hour or 13.176°/day or one complete rotation in inertial space every 27.32 days. The rotation rate is one twenty-seventh that of the Earth's, and the Moon's orbital plane is inclined about 5° 8' with respect to the ecliptic (plane of Earth's orbit). These parameters affect the strategy for obtaining full global imagery coverage. The approach in this conceptual design is to image the Moon as it rotates every 29.53 days underneath the orbiting sensor, which is essentially fixed in inertial space (Krueger, 1965; A.P. Colvocoresses, personal communication, 1988; Batson, 1987; Greely and Batson, 1990).

Orbital Characteristics for Lunar Satellites

For satellite lunar mapping and reconnaissance missions, near-polar, near-circular orbits are desired because of the

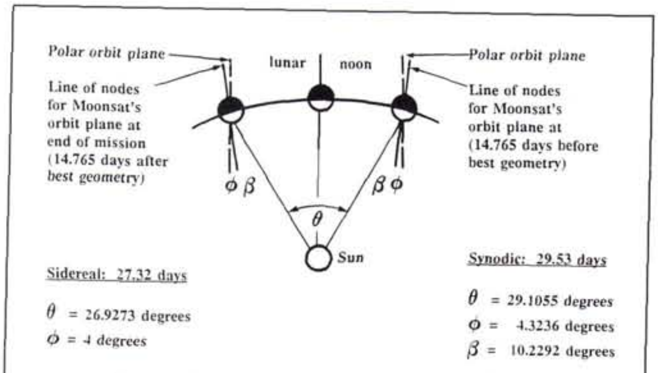


Figure 1. Lunar geometry–One lunar day.

need for global coverage, yet the orbits must have sufficient scene illumination from the sun. Scene illumination must remain as constant as possible throughout the imaging cycle. Unfortunately, the precession of Moonsat's orbital plane is very slow as compared to the Moon's rotational rate. Imposing the sun-synchronous condition for lunar orbits, as can be done for Earth orbits, is not feasible for producing near-polar, sun-synchronous orbits for the Moon. It is suggested that an inclination of 104° is a reasonable compromise; it is near-polar and accommodates the need for solar illumination.

Precession of Line of Nodes

The precession of a satellites line of nodes due to oblateness of the body is given by Battin (1987): i.e.,

$$\dot{\Omega} = -\frac{3}{2} J_2 \left(\frac{r}{p}\right)^2 n \cos i, \quad p = a(1-e^2), \qquad n = \frac{\sqrt{\mu}}{a^{3/2}} \tag{5}$$

where

J_2 = coefficient pertaining to oblateness of the Moon (0.000207108),
μ = the lunar gravitational mass (4902.780 km³/sec²),
r = mean radius of the lunar sphere (1737.63 km),
H = orbital height above the mean radius of the Moon (100 km for Moonsat),
a = radius of the orbit above the Moon's center of mass $= (r + H)$,
e = eccentricity of the orbit (zero for circular orbits), and
i = inclination of the orbital plane to the equator.

Now, substituting J_2, μ, r, and a into Equation 5, it can be shown that

$$\dot{\Omega} = -40.615 \left(\frac{r}{a}\right)^{3.5} (1-e^2)^{-2} \cos i \left[\frac{\text{degrees}}{\text{lunar day}}\right] \tag{6}$$

The Moon's oblateness is much less than the Earth's. The rather extreme oblateness of the Earth arises due to the fact that the Earth rotates at the high angular velocity of 360°/day, in contrast to the Moon, which rotates at the relatively slow angular rate of 360°/(27.32 days). As a consequence of this and the fact that the Moon has no oceans, the Moon has a much more spherical shape. Therefore, the oblateness-induced orbital precession is much less. This perturbation has historically been depended upon for Earth-centered orbits to cause near-polar orbits to precess about a degree/day and, therefore, provide sun-synchronous orbits attractive for many Earth-sensing missions.

For example, to obtain an exact sun-synchronous orbit for 100 km above the Moon, Ω would be

$$\dot{\Omega} = \left(\frac{27.32}{365.26}\right) 360 = 26.9266 \left[\frac{\text{degrees}}{\text{sidereal day}}\right]$$

and, for $a = 1867.63$ km and $e = 0$, Equation 6 gives $i = 143.745°$. This is not an acceptable orbital inclination for lunar mapping, because the orbit does not pass sufficiently near the poles.

The geometry shown in Figure 1 is a view from above the ecliptic plane. The sketch is useful for orbit design because it shows the line of nodes of Moonsat's orbit. The orbital plane can be allowed to precess due to lunar oblateness through a sidereal angle of 2ϕ while the moon moves in its orbit one sidereal lunar day ($\theta = 26.9266°$). This allows use of the perturbation to assure sunlight conditions, although ϕ is less than the ideal, $\theta/2 = 13.4633°$. For example, if $\phi = 4°$ is selected, then $\Omega = 2\phi = 8°$ per lunar day, and substituting this into Equation 6 gives the resulting near-polar inclination $i = 103.862°$. Selecting $\phi = 4°$ leads to an inclination $i = 104°$, which leans the orbital plane toward the sun, but is near enough polar to be considered a near-polar mission. The above is based upon the mission lasting one sidereal month, or 27.32 days. In order to create the opportunity to map all of the Moon with consideration for sun lighting, it is necessary that the mapping mission last at least one synodic month, or 29.53 days. This necessitates starting early and ending late with respect to the geometry of Figure 1. The properly modified mission duration is 2.21 days longer, beginning 1.105 days "early" and ending 1.105 days "late" with respect to the sidereal day. If the 104° orbital inclination is retained and, therefore, the corresponding Moonsat precession rate of 8° per lunar month, then it is apparent that ϕ of Figure 1 is increased by (29.53 ÷ 27.32) (4.0°) = 4.3236° at the beginning and ending of this longer (29.53 days) mission. In Figure 1, $\beta = \frac{\theta}{2} - \phi$. Using the synodic values in Figure 1, $\beta = 10.2292°$. Therefore, 10.2292° will be the largest angular displacement of the sun above or below the Moonsat orbit plane. This results in the Sun always being within 10.2292° of the sun-synchronous case. The orbital analysis was done by J. Junkins (personal communication, 1992).

In summary, the computations for a compromise away from the sun-synchronous orbit and toward the near polar inclination (i) yields $i \approx 104°$. If the imaging mission is to be carried out for one synodic lunar month to acquire global coverage, the sun will lie in the orbital plane 14.765 days after starting the mission. Aligning Moonsat's orbital plane with the sun at the midpoint of the mission is open to question. Optimal illumination is clearly terrain-dependent. It may be that selecting $i = 90°$ would be adequate, and it certainly provides optimum geometric coverage. More analysis is warranted on the tradeoffs of selecting inclination. Regarding sun angle, Kruger (1965) showed that good sun lighting occurs at sun altitudes of 15° to 45°. It may be best to run Moonsat over several cycles and take advantage of best lighting as it occurs in each cycle.

Moonsat's Orbital Trace Pattern

Perhaps the most important factor in sizing Moonsat's orbit is the spacecraft's subsatellite trace on the surface of the rotating Moon. The criterion is that illumination changes as little as possible between adjacent swaths and the height must be appropriate to the requirements: i.e.,

$$S = 360°/Q \tag{7}$$

where S = trace shift-distance (longitudinal) between two successive equatorial crossings

Q = trace repetition parameters, I, K, and N – Orbits/lunar day

In this case, $S = 360° \div 361$ orbits $= 0.997°$ per orbit.

In general Q can have the form $Q = I - K/N$ (8)

where I = integer number of orbits in a lunar day and I sets the height H, and K/N = a rational fraction reduced to lowest terms.

If Q is an integer with no K/N fraction, Q results in a trace pattern which repeats itself every lunar day. Otherwise, the denominator of the fraction, N, defines the number of lunar days it takes the ground trace to repeat itself. This is called the repeat cycle. The numerator K is related to the number P, where P is the number of integral segments between traces laid down on successive lunar days. Each trace shift (S) is divided into R integral segments; where $R = I(N) - K$ (Gerding and Jenkin, 1971; Light, 1990).

$$\text{If } \frac{K}{N} \le \frac{1}{2}, \text{ then } P = K \text{ but,}$$
$$\text{if } \frac{K}{N} > \frac{1}{2}, \text{ then } P = N - K.$$

Orbit Period and Height for Moonsat

A cartographer's preference is an orbit that provides global coverage in a sequential manner; that is, a swath is collected on orbit 1 and then orbit 2 collects the next adjacent swath, thus providing contiguous swathing coverage around the lunar globe. A lunar orbit of 100 km is high enough to be above the mountains and low enough to permit high spatial resolution with reasonably sized optics. With an orbital height of 100 km, the satellite will cover the Moon in approximately 361 orbits, and the lunar rotation per orbital period is on the order of 30 km, which leads to a reasonable swath width.

If orbits in the neighborhood of 100 km altitude (54 nautical miles) are selected, the orbit period (T) must satisfy the relation

$$T = \frac{2{,}551{,}392 \text{ sec/lunar synodic day}}{\mathrm{I} - K/N} \tag{9}$$

where

2,551,392 = number of seconds in one lunar synodic day (29.53 Earth days/lunar day × 86,400 sec/Earth day),

N = number of lunar synodic days in the repeat cycle,

K = number of swaths skipped on adjacent lunar synodic days, and

I = integer number of orbits per lunar synodic day. Setting I = 362 scales the height (H) to approximately 100 km.

Using Equation 9, the approximate orbital period (T) for one repeat cycle to cover the lunar globe is

$$\begin{aligned} T &= \frac{2{,}551{,}392}{362 - \frac{1}{1}} \text{ sec} \\ &= 7067.2096 \text{ sec/orbit} \\ &= 117.78683 \text{ min/orbit} \end{aligned} \tag{10}$$

Given the period (T) and assuming circular orbits, an equation to solve for the orbital height (H) above the mean radius (r) of the Moon is

$$a = r + H = \left[\mu\left(\frac{T \text{ sec}}{2\pi}\right)^2\right]^{1/3} \tag{11}$$

Therefore, from Equation 11,

$r + H = 1837.3541$ km

$H = 1837.35 \text{ km} - 1737.63 \text{ km}$

$= 99.72 \text{ km} \simeq 100 \text{ km}$

Also, from Equation 8, the number of orbits (R) in the repeat cycle (Q) to cover the Moon in one lunar synodic day (29.53 days) is

$R = I(N) - K.$

For Moonsat,

$R = 362\ (1) - 1$

$= 361$ orbits to cover the Moon in one lunar synodic day.

Sensor Swath Width

Considering the Moon as a sphere, the circumference (C) of the Moon at the equator is

$C = 2\pi\ (1737.63 \text{ km})$

$= 10{,}917.851$ km

Then, due to the Moon's rotation per each Moonsat orbit, the width (W) of each orbital pass is

$$\begin{aligned} W &= \frac{2\pi r \sin i}{361 \text{ orbits}} \text{ km/orbit} \\ &= \frac{10{,}917.851 \text{ km (sin 103.862 degrees)}}{361 \text{ orbits}} \\ &= 29.363 \text{ km/orbit at the equator} \end{aligned} \tag{12}$$

The actual sensor swath width (SW) must be some comfortable amount larger than W to provide image sidelap and allow some variation in the orbit due to various perturbations. Expanding the 29.363 km to 35 km yields a sensor swath width that is small compared to Earth satellites, but the 35-km swath width will allow a reasonable data rate for transmitting data back to Earth.

Florensky *et al.* (1971) defined appropriate scales and map sheet sizes for mapping the Moon. Table 4 presents their recommendations. In Table 4, the dimensions for a 1:50,000-scale map of a lunar area is 0°40' by 1°00', which is 20.5 km latitude by 30.5 km longitude. Therefore, a scene size of 25 km along track and 35 km wide is more than adequate to cover one map sheet at 1:50,000 scale and allow for some orbital perturbation. Also, Inge and Batson (1992) provide an excellent documentation of indexes for the Moon and Planets.

Geometric Configuration of Sensors

Band 1, Moonsat's panchromatic band (see Figure 2), is configured in convergent stereo mode. The Z-coordinates (elevations) are the intersections of the converged sensor's rays at the lunar surface. The vertical, down-looking sensor in the

Table 4. Lunar Map Scales and Dimensions (from Florensky et al., 1971)

Map Scale	Frame dimensions Lat ϕ	Long λ	Frame dimension at maps scale (cm) ϕ	λ	Frame dimensions (in km) ϕ	λ	Sheets: number in the preceding scale	Sheets: number in preceding 1:1,000,000 scale
1:1,000,000	16°00'	20°00'	49	61	490.0	610.0	1	1
1:500,000	8°00'	10°00'	49	61	245.0	305.0	4	4
1:250,000	4°00'	5°00'	49	61	122.5	152.5	4	16
1:100,000	1°20'	2°00'	40	61	40.0	61.0	120	120
1:50,000	0°40'	1°00'	41	61	20.5	30.5	4	480
1:25,000	0°20'	0°30'	40	61	10.0	15.2	4	1,920
1:10,000	0°10'	0°10'	50	50	5.0	5.0	6	11,520

middle of Figure 2 represents the other five multispectral images (not in stereo). The two rectangular array sensors looking out to the celestial sphere are for sensing stars from which precise attitude can be determined. Because the suggested 104° orbit is 14° off the poles, the sensor may be designed to tilt off-nadir for imaging at the poles.

Attitude Sensor

A preferred way of sensing attitude is by using star sensors. Star cameras were used in the Apollo 15, 16, and 17 missions. Star sensors are available off-the-shelf from the electro-optical industry. Assume that a rectangular array CCD sensor can detect star light of magnitude five or lower and that there are approximately 5,400 such stars distributed uniformly over the celestial sphere, the calculated star density (P) is

$$P = \frac{5{,}400 \text{ stars/sphere}}{41{,}253 \text{ square degrees/sphere}} \simeq \frac{0.13 \text{ stars}}{\text{square degree}}. \qquad (13)$$

For a rectangular star sensor field of view, 7° × 9° = 63 square degrees, one can expect an average of 8.2 stars in the sensor's field of view at any time (Junkins and Strikwerda, 1981). Light (1990) showed that typical sensor attitudes of ±2 to 4 arc seconds are possible; this star-derived attitude can be related to the Moon-looking panchromatic sensors employing precalibration of the sensor geometric configuration and synchronized timing. As a star transits across the rectangular arrays, a continuous estimating function can compute attitude. The attitude orientation matrix computed in the right ascension, declination system has to be transformed into the lunar coordinate system. The transformed attitude can be related to the stereo ground-looking sensors. This star derived attitude becomes the orientation for the stereo models.

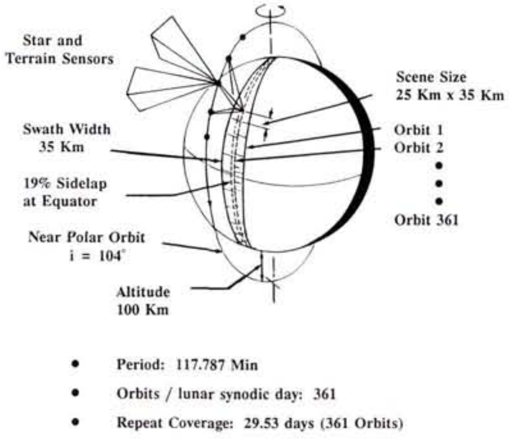


Figure 2. Moonsat.

Terrain Sensors

The proposed configuration for Moonsat's convergent stereo sensors is based upon a number of scientific requirements:

- 4-metre spatial resolution,
- in-orbit stereo capability,
- scene size sufficient to cover a 1:50,000-scale image map sheet, and
- geometric quality sufficient for digital elevation models accurate to ±3 m.

Solid state linear arrays with detector size of 13 μm would require 8,750 detectors with a 20° angular field of view to cover the 35-km swath width. The focal length required for sensing 4-m pixels on the lunar surface with convergent stereo-sensors is approximately 0.4 m. These parameters are all well within the state-of-the-art for the sensor industry. The high resolution stereo camera proposed as a candidate for the mission to the Moon by Neukum (1990) specifies a detector size of 7 μm. If 7-μm detectors are sufficient, the focal length of the sensor would be reduced by about 50 percent.

Multispectral Sensors

Table 3 shows the spectral wavelengths and spatial resolution of 10 m for each of the five sensors. These sensors are nadir looking with 3,500 detectors to cover the 35 km swath width. The focal lengths for the sensors will range from 0.13 m to 0.23 m.

Sensor Position on Orbit

The preferred method for tracking satellites over the years has been doppler radar tracking. Doppler was successfully used in the Apollo program during the 1960s. Now that the Global Positioning System (GPS) is about complete, satellite positioning around the Earth may resort to using the GPS constellation where feasible. GPS range accuracy for a satellite inside the constellation is $\sigma = \pm 8$ metres. Because the Moon is, on average, at least 20 times further away than an Earth satellite, the moon orbiting receiver to GPS satellite geometry would be weak. The result is position dilution of precision (PDOP). Unfortunately, both doppler tracking and the GPS have this similar drawback. In either case, tracking can be used as a constraint on the 3D behavior of the Moonsat, but, because of the small subtended angle between Moonsat

TABLE 5. DATA VOLUME AND RATE FOR SCENES 25 BY 35 KM

Ps (m)	Pixels in scene	Pixels × 8 bits/pixel	Bands to transmit	Bits per scene	Compressed 8 to 4 bits	Data rate (Mbps)
4	5.47×10^{7}	4.38×10^{8}	2*	8.75×10^{8}	4.38×10^{8}	27
10	8.75×10^{6}	7.00×10^{7}	5	3.50×10^{8}	1.75×10^{8}	11

*stereo panchromatic

Total data rate 38

and the GPS constellation, a computed *X,Y,Z*-coordinate may have a large PDOP, and may be difficult to obtain. This depends on GPS transmitting outward as well as inward which may not be the case. In fact, an experiment or simulation study is warranted to determine GPS's application to satellite positioning outside its constellation. For Moonsat, sensor positions as a function of precise time (0.0001 sec) for each line of detectors is needed. This position integrated with the star and terrain sensors all synchronized with precise time form the basis for knowing both position and attitude of Moonsat. These position and attitude data would serve as vital inputs to computing a unified lunar control point network (Brown, 1968).

Data Volume and Rate

The two convergent stereo terrain sensors will sample on 4-m centers across track for the panchromatic stereo bands, and the nadir-looking sensors will sample on 10-m centers for bands 2, 3, 4, 5, and 6 as shown in Table 3. Data volumes are computed by Equation 16 and are shown in Table 5.

Orbital Velocity: Circular Orbits

For calculating data rates, it is essential to know the satellite velocity (V_s), and the velocity of the satellite's track on the surface (V_g).

$$V_s = \left[\frac{\mu}{r + H}\right]^{1/2} \text{ km/sec} \tag{14}$$

Substituting the appropriate values defined in Equation 5,

$$V_s = 1.63 \text{ km/sec}$$

Then

$$V_g = \left[\frac{V_s r}{r + H}\right] \text{ km/sec} \tag{15}$$

$$= 1.54 \text{ km/sec}$$

Data Rate for Moonsat

$$\text{Pixels per scene} = \left(\frac{25 \times 10^3 \text{ m}}{\text{Ps m}}\right)\left(\frac{35 \times 10^3 \text{ m}}{\text{Ps m}}\right) \tag{16}$$

where Ps = pixel size.

The satellite velocity on the lunar surface (V_g) is 1.54 km/sec. The time to image one 25-km scene; 25 km ÷ 1.54 km/sec = 16.24 sec. Data compression rates going from 8 to 4 bits are well within industry capabilities. The final data rate = compressed data ÷ 16.24 sec, which yields 38 Mbps for all sensors transmitting.

Moonsat Summary

In summary, Moonsat proposes six essential characteristics that should meet data requirements for 1:50,000-scale topographic products (including DEMs) and image map data suitable for GIS applications. These data would be an ideal set for lunar modeling and research useful for the entire international community. The six essential Moonsat characteristics are as follows:

- 4-m ground pixel size in stereo to support topographic mapping at 1:50,000 scale;
- stereoscopic coverage with the panchromatic band in the same orbit;
- precise satellite position, attitude, and calibration;
- broad area coverage (25 by 35 km scene);
- contiguous global coverage every lunar month; and
- multispectral bands nearly equivalent to those used by the Landsat TM and SPOT and applicable to lunar science.

Specifications for Moonsat are as follows:

Mission: Imaging the Moon for topographic GIS, mapping, and lunar science applications at 1:50,000 scale and smaller.

Orbit:	Type	Circular
	Inclination	Near polar, $i \simeq 104°$
	Altitude	100 km
	Period	117.787 minutes
	Orbits per synodic lunar day	361
	Repeat cycle	29.53 days, one synodic lunar month
	Velocity (V_s)	1.63 km/sec
	Ground velocity (V_g)	1.54 km/sec
	Number of orbits to cover lunar globe	361
Terrain sensor:	Types	Linear array pushbroom each band
	Swath width	35 km (covers one 1:50,000-scale map)
	Pixel size	4 m for panchromatic band 10 m for 5 multispectral bands
	Focal length	≥ 0.4 m
	Array Scan	Convergent stereosensor configuration (panchromatic) Vertical sensor configuration (multispectral)
	Field of view	20° for 35 km swath
	Convergence angle	Approximately 30° depending on *B/H* ratio
	Detectors in array	8,750 for panchromatic band 3,500 for multispectral bands
	Sensor positioning	GPS, if feasible, or Earth-based tracking
Attitude sensor:	Type	Rectangular arrays (2), time synchronized
	Stars	Measures stars magnitude 5 or lower traversing array realtime
	Output	Attitude as a function of time
	ω, φ, κ	±2 to 4 arc seconds

Sensitivity:		
Band No.	Spectral Band/ Centers	Color
1.	0.40-0.80	Panchromatic for stereomapping
2.	0.40	Blue
3.	0.56	Green
4.	0.70	Red
5.	0.95	NIR
6.	1.20	NIR
Quantization:		
Level:	8 bits per pixel	256 shades of gray
Scene size:	25 by 35 km	Scene covers a 1:50,000-scale map sheet which is 0°40' by 1°00'
Data rate:	38 Mbps	Downlink compressed 8 to 4 bits (50 percent)
Sensor timing:	0.0001 sec	Relative timing

Acknowledgments

The author is indebted to John L. Junkins, Texas A&M University, for orbit inclination analysis (Figure 1). Also, Larry Rowan of the U.S. Geological Survey provided information on spectral sensing, and Ray Batson and Frederick Doyle (retired) of the U.S. Geological Survey offered constructive suggestions on an early draft of this paper.

References

Asker, J.R., 1992. U.S. Draws Blueprints for First Lunar Base, *Aviation Week and Space Technology*, August 31, 1992, pp. 47–51.

Battin, R.H., 1987. *An Introduction to the Mathematics and Methods of Astrodynamics*, American Institute of Aeronautics and Astronautics, Inc., New York, New York, 504 p.

Brown, D.C., 1968. A Unified Lunar Control Network, *Photogrammetric Engineering*, 34(12):1272-1292.

Batson, R.M., 1987. Digital Cartography of the Planets: New Methods, its States and its Future, *Photogrammetric Engineering & Remote Sensing*, 53(9):1211-1218.

Charette, M.P., T.B. McCord, C. Pieters, and J.B. Adams, 1974. Application of Remote Spectral Reflectance Measurements to Lunar Geology Classification and Determination of Titanium Content of Lunar Soils, *Journal of Geophysical Research*, 79(11):1605-1613.

Colvocoresses, A.P., 1982. An Automated Mapping Satellite System (Mapsat), *Photogrammetric Engineering & Remote Sensing*, 48(10):1585-1591.

Doyle, F.J., 1970. Photographic Systems for Apollo, Photogrammetric Engineering, 36(10):1039-1044.

———, 1992. Report of the Planetary Cartography Working Group, Presentation to Congress of the International Society of Photogrammetry and Remote Sensing, Washington, D.C., 2-14 August 1992.

Florensky, K.P., A.A. Gurshtein, V.I. Korablev, L.M. Bougaevsky, and K.B. Shingareva, 1971. Classification, Scales Sequence and Nomenclature of Lunar Maps, *The Moon*, D. Reidel Publishing Company/Dordrecht-Holland, 3:78-89.

Gerding, R.B., and K.R. Jenkin, 1971. Ocean Color Measurements Utilizing a Noon Orbit for Earth Resources Satellite Applications, *Proceedings of the SPIE Seminar: Remote Sensing of Earth Resources and the Environment*, November 1971, Palo Alto, California, 27:101-109.

Greeley, R., and R.M. Batson, 1990. *Planetary Mapping*, Cambridge University Press, Cambridge, New York.

Head, J.W., C. Pieters, T. McCord, J. Adams, and S. Zisk, 1978. Definition and Detailed Characterization of Lunar Surface Units Using Remote Observations, *Icarus*, 33:145-172.

Inge, J.L., and R.M. Batson, 1992. *Indexes of Maps of the Planets and Satellites*, NASA Technical Manual 4395, August 1992, NASA Code JTT, Washington, D.C.

Junkins, J.L., and T.E. Strikwerda, 1981. *Star Pattern Recognition and Spacecraft Attitude Determination*, Virginia Polytechnic Institute and State University Report for Engineer Topographic Laboratories, ETL-0260, Ft. Belvoir, Virginia.

Krueger, M.W., 1965. Some Design Considerations for Lunar Orbital Photographic Systems, *Proceedings of Semi-annual Convention*, American Society of Photogrammetry, Dayton, Ohio, 22-24 September, pp. 139-166.

Light, D.L., 1970. Extraterrestrial Photogrammetry at TOPOCOM, *Photogrammetric Engineering*, 36(3):260-272.

———, 1972. Photo Geodesy From Apollo, *Photogrammetric Engineering & Remote Sensing*, 38(6):574-587.

———, 1980. Satellite Photogrammetry, *Manual of Photogrammetry, Fourth Edition* (C. Slama, editor), American Society of Photogrammetry, Falls Church, Virginia, pp. 899-923.

———, 1990. Characteristics of Remote Sensors for Mapping and Earth Science Applications, *Photogrammetric Engineering & Remote Sensing*, 56(12):1,613-1,623.

NASA, 1973. *Apollo 17 Preliminary Science Report*, NASA SP-330, U.S. Government Printing Office, Washington, D.C., pp. 2-3.

Nash, D.B., and J.E. Conel, 1974. Spectral Reflectance Systematics for Mixtures of Powdered Hypersthene, Labradorite, and Ilmenite, *Journal of Geophysical Research*, 79(11):1615-1621.

Neukam, Gerhard, 1990. *HRSC: High Resolution Stereo Camera, Mars 94 Mission*, German Aerospace Research Establishment, DLR, OE-PE, Part B.

———, 1992. Planetary Remote Sensing with the Galileo Space Probe, *DLR-Nachrichten*, (66):32-37.

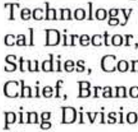
Paine, T.O., 1986. *The Report of the National Space Commission, Pioneering The Space Frontier*, Bantam Books, Inc., 666 Fifth Avenue, New York, pp. 138-140.

Soderblom, L.A., and J.M. Boyce, 1976. Distribution and Evolution of Global Color Provinces on the Moon, *Lunar Science*, 7:822-824.

Stafford, T.P., 1991. *Report of the Synthesis Group on America's Space Exploration Initiative*, Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., p. iv.

Star, J., and J. Estes, 1990. *Geographic Information Systems, An Introduction*, Prentice Hall, Englewood Cliffs, New Jersey, pp. 12-13.

(Received 5 January 1993: accepted 2 June 1993)



Donald L. Light

Don Light has a BS Degree in Geodetic and Cartographic Science from The George Washington University and a masters level diploma in Strategy and Management from the U.S. Naval War College. Don served in the U.S. Army 30th Engineer Topographic Battalion (2 years), the Defense Mapping Agency (25 years), and the U.S. Geological Survey (USGS) since 1980. His years of experience have spanned nearly all phases of topographic mapping, photogrammetry, remote sensing, and systems development for automating mapping systems. Significant assignments have been Chief, Advanced Technology Division, Defense Mapping Agency, HTC; Technical Director, Defense Mapping School; Space Applications Studies, Congressional Office of Technology Assessment; Chief, Branch of Systems Development, USGS, National Mapping Division; and currently as Chief, Branch of Contract Management, where he manages the National Aerial Photography Program. Don has published numerous articles on remote sensing systems for the Earth and Moon and is the author editor of Chapter 17, Satellite Photogrammetry in the

ASPRS *Manual of Photogrammetry*. In 1992, Don was awarded the Department of the Interior's Meritorious Service Award. He also teaches photogrammetry part time at the George Mason University, Fairfax, Virginia, and is a graduate of the Federal Executive Development Program, 1980.

International Symposium on Spatial Accuracy of Natural Resource Data Bases

Unlocking the Puzzle

16-20 May 1994, Williamsburg, Virginia

Russell G. Congalton, Editor

1994. 280 pp. $65 (softcover); ASPRS Members $40. Stock # 4536.

The International Symposium on Spatial Accuracy of Natural Resource Data Bases was organized to bring together a group of individuals with common interest in the spatial accuracy of natural resource data bases so that the latest information could be exchanged, and to develop communication pathways that will hopefully long outlive the meeting.

The workshop was sponsored by the International Union of Forestry Research Organizations Forest Inventory and Monitoring Subject Group (S4.02) and the American Society for Photogrammetry and Remote Sensing (ASPRS). The workshop was also endorsed by the Society of American Foresters, GIS Working Group.

This volume of proceedings is a collection of 32 papers that were presented at that meeting, and they dealing with almost every aspect of spatial accuracy in the natural resources area.

Topics Include:

Session 1 -	Importance of Accuracy I
Session 2 -	Importance of Accuracy II
Session 3 -	Accuracy of Basic Data I
Session 4 -	Accuracy of Basic Data II
Session 5 -	Example Applications I
Session 6 -	Remote Sensing I
Session 7 -	Terrain DEM's
Session 8 -	Dealing With Accuracy I
Session 9 -	Dealing With Accuracy II
Session 10 -	Remote Sensing II
Session 11 -	Dealing With Accuracy II
Session 12 -	Example Applications III
Session 13 -	Example Applications IV
Posters	

For details on ordering, see the ASPRS store in this journal.