CONCEPTUAL DEVELOPMENT OF A GROUND-BASED RADIO-BEACON NAVIGATION SYSTEM FOR USE ON THE SURFACE OF THE MOON

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Dear Dr. Fowler:

Attached is our final report, Conceptual Development of a Ground-based Radiobeacon Navigation System for Use on the Surface of the Moon. This report includes discussion of project criteria, alternate designs, final design solution, and recommendations. The final design is based on a spread-spectrum radiobeacon navigating technique.

We have enjoyed working with you and appreciate your time, support and advice. We look forward to seeing you at our project presentation, scheduled on Tuesday, April 26, 1988, at 10:00 a.m. in Room 4.110 of the Engineering Teaching Center. You are also invited to a catered luncheon at noon.

Thank you for your assistance throughout the semester.

Sincerely,

Andrew J. Beggins

Andrew J. Beggins, Team Leader

Lora Canney

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ABSTRACT

CONCEPTUAL DEVELOPMENT OF A GROUND-BASED RADIO-BEACON NAVIGATION SYSTEM FOR USE ON THE SURFACE OF THE MOON

A long-term goal of NASA is the establishment of a manned lunar base to support several objectives: mining and utilization of lunar resources, maintenance of the space platforms, scientific research of the Moon and its environment, and future missions to Mars. To effectively develop the lunar surface, astronauts will require a navigation system to locate their positions when out of sight range of the base facility.

The Universities Space Research Association asked the design team to develop such a navigation system. The design team researched four navigational methods for adaption to the lunar surface: celestial, satellite, inertial, and radio-beacon. Evaluation of the four methods led the design team to choose a spread-spectrum radio-beacon navigation system. The design team developed the system for use in preliminary phases of lunar base operation with the assurance that it can be expanded for use in later phases. The principle of operation, specifications (power requirements, operating frequencies, weight, size, and range) and modifications of the system for lunar use are discussed.

The advantages of this system over the others considered are: ease of implementation and operation, low cost of transport (light-weight), low maintenance requirements, and expandability.

KEYWORDS: lunar, radio-beacon, navigation

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INTRODUCTION

One of the many responsibilities of the National Aeronautics and Space Administration (NASA) is to plan for the nation's future in space exploration and industrialization. A major part of this task is to encourage the development of technologies needed to support NASA's future goals. The nation's universities are prime sources of the knowledge necessary to develop these required technologies. Hence, the Universities Space Research Association (USRA) was established to take advantage of the bright, uninhibited minds of university students. The University of Texas at Austin is one institution currently involved in the USRA program. Through this program, senior and graduate level students in the mechanical and aerospace engineering departments are working to develop the technologies that will help support NASA's far-reaching goals in space exploration. One of these goals is the establishment of a lunar colony. To effectively develop the lunar surface, astronauts will require a navigational system to locate their relative positions. This report presents the selection and conceptual development of such a navigational system.

The first section of the report contains background information on the project as defined by USRA, the criteria for an effective navigation system, and the methodology used to develop the final project solution. The next section describes the alternate navigation systems considered by the design team for adaption to the lunar surface. The following sections present the method used to select the final design and the development of that design, including principle of operation, specifications, and proposed modifications of the system for lunar use. The final section contains a summary of the project solution, a description of how the solution meets the project criteria, and recommendations.

BACKGROUND

A long-term goal of NASA is the establishment of a lunar colony. This colony will support several objectives: mining and utilization of lunar resources, maintenance of space platforms, scientific research of the Moon and its environment, and advanced missions to Mars. The untapped supply of resources in the lunar environment and its geologic structures provides incentive for lunar endeavors. Some key resources include liquid oxygen and metals such as iron and titanium. Efficient use of these elements will aid in the future industrialization of space. A lunar base will also provide support for space platforms used in low-Earth orbit operations, observation of the Earth, and interplanetary travel. Scientific research of the Moon offers advancement in many areas including astronomy, lunar geology, astrophysics, geophysics, materials science. Eventually, a lunar colony may be used to test the feasibility of future colonies on Mars. The successful development of a lunar colony will demonstrate not only the human ability to live and produce in an outer-space environment but also the potential utilization of extraterrestrial resources.

In order to continue lunar exploration and development, astronauts will require a method to accurately locate their positions on the Moon. Lunar navigation has been ignored in previous missions because it was not a pressing issue. Navigation was accomplished by simply following the tracks left by the lunar rover. However, as moon-based operations expand, this technique will become difficult and eventually impossible. Through Dr. W.T. Fowler, in conjunction with USRA, the concept of a lunar navigation system was submitted for development to The University of Texas at Austin Senior Mechanical Engineering Design Projects Program .

DESIGN CRITERIA

Our design team identified the following criteria as necessary for effective navigation of the lunar surface:

1. The system should be convenient for an astronaut to use within the physical limitations of full space gear.
2. The system must not be affected by the abnormalities of the lunar surface or environment.
3. The system should provide sufficient coverage for preliminary lunar base operations.
4. The system should be readily expandable to accommodate the anticipated growth of lunar operations.
5. The system should be lightweight and relatively easy to install and maintain.
6. The system should be accurate within sight distance.

DESIGN METHODOLOGY

The design team investigated the aspects of general navigation, including celestial techniques, satellite systems, inertial navigation, and radio-beacon methods. Initially, research was conducted to determine the effects of the moon's surface and its environment on lunar navigation. This included an on-line computer search of the engineering and science indexes as well as consultations with experts on navigation and the Moon. Some primary considerations included:

1. Radiation effects on system operation.
2. Abnormalities in the Moon's geometry and orbit.
3. The effect of micrometeorites on system hardware.
4. The Moon's nonhomogeneous gravity field.
5. Little or no lunar magnetic field.

The acquired information was used to analyze various navigational systems that met the project criteria. These systems were then evaluated using a decision matrix to determine the most feasible method for development into a final design. The methodology used to develop the best design is outlined below:

1. Specification of guidelines concerning the mobility of astronauts on the lunar surface.
2. Identification and explanation of the physical operation and specifications of the system including power requirements, operating frequency, and range.
3. Proposal of modifications to the system for use in the harsh lunar environment.
4. Suggestion of a back-up method for use in emergency "lifeboat" situations.

ALTERNATE NAVIGATION SYSTEMS

The design team considered four navigational methods for adaption to the lunar surface:

1. Celestial navigation
2. Satellite navigation
3. Radio-beacon systems
4. Inertial techniques.

When choosing a navigation system, a user must be concerned with operational suitability, cost, coverage, reliability, and integrity (i.e., all-weather operation and freedom from atmospheric interference). These concerns must be taken into account for efficient navigation of the lunar surface. This alternate designs section presents an overview of the systems mentioned above and the advantages and disadvantages of each.

CELESTIAL NAVIGATION

The process of determining position from celestial observations is essentially the same for all spherical bodies. As the Earth and the Moon are similar spheres, conventional celestial navigation methods used on Earth may be applied to determine the position of a lunar observer.[14*] The practical

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* All references in this report refer to the numbered references on pages 71-73.

application of celestial techniques to lunar navigation is concerned with certain differences in terrestrial and **selenographic** aspects.[14]

CELESTIAL NAVIGATION ON THE EARTH - A BRIEF EXPLANATION

To an observer on the Earth's surface, the Earth appears to be stationary at the center of the universe, and the visible celestial bodies appear to be on the inner-side of an infinite extension of the Earth's physical sphere. Thus, within this celestial framework, the position of a celestial body may be defined by its celestial latitude, or **declination**, and its celestial longitude, or **hour angle**. The Earth rotates at a uniform rate (approximately one revolution per 24 hours) from east to west so that the celestial bodies appear to rise in the east and set in the west.

The **vernal equinox**, or the **first point of Aries**, is defined by a point on the **celestial sphere** where the **celestial equator** (the plane of the Earth's equator) and the **ecliptic** plane (the plane defined by the orbit of the Earth about the Sun) intersect (see Figure 1).[33] Due to the Earth's rotation, the vernal equinox passes over the Greenwich **Meridian** approximately once every 24 hours. This allows the charting of star **altitudes**/locations relative to the Greenwich Meridian.

Two Star Method of Celestial Navigation

One method of celestial navigation is the Two-Star Sight Method which, in its simplest form, determines an observer's longitude and latitude from the altitudes of two identified stars observed at a known Greenwich Mean Time (GMT) on a known date (see Figure 2).[30] The altitude of a celestial body is the

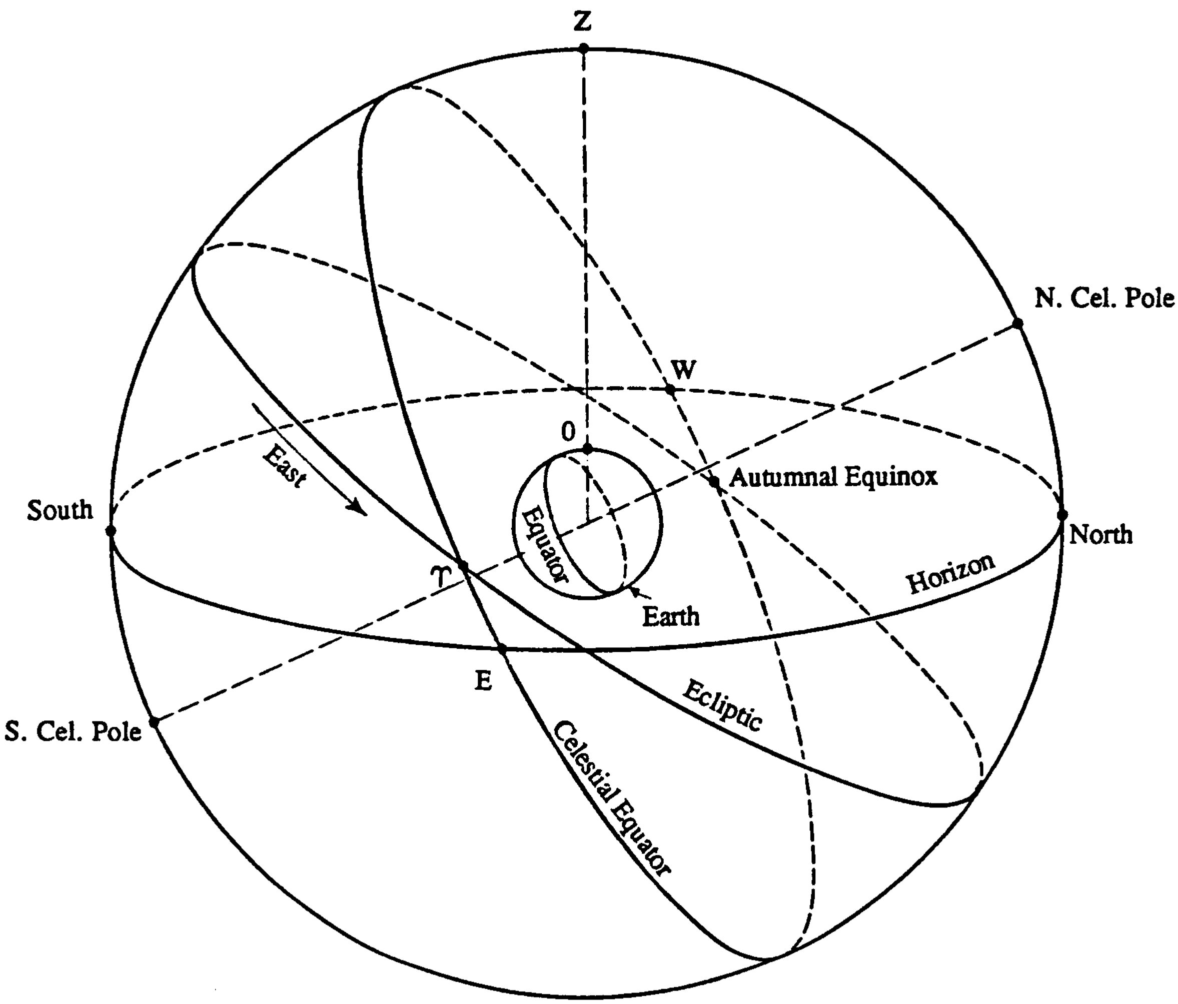


Figure 1: CELESTIAL SPHERE WITH ECLIPTIC AND EQUINOXES

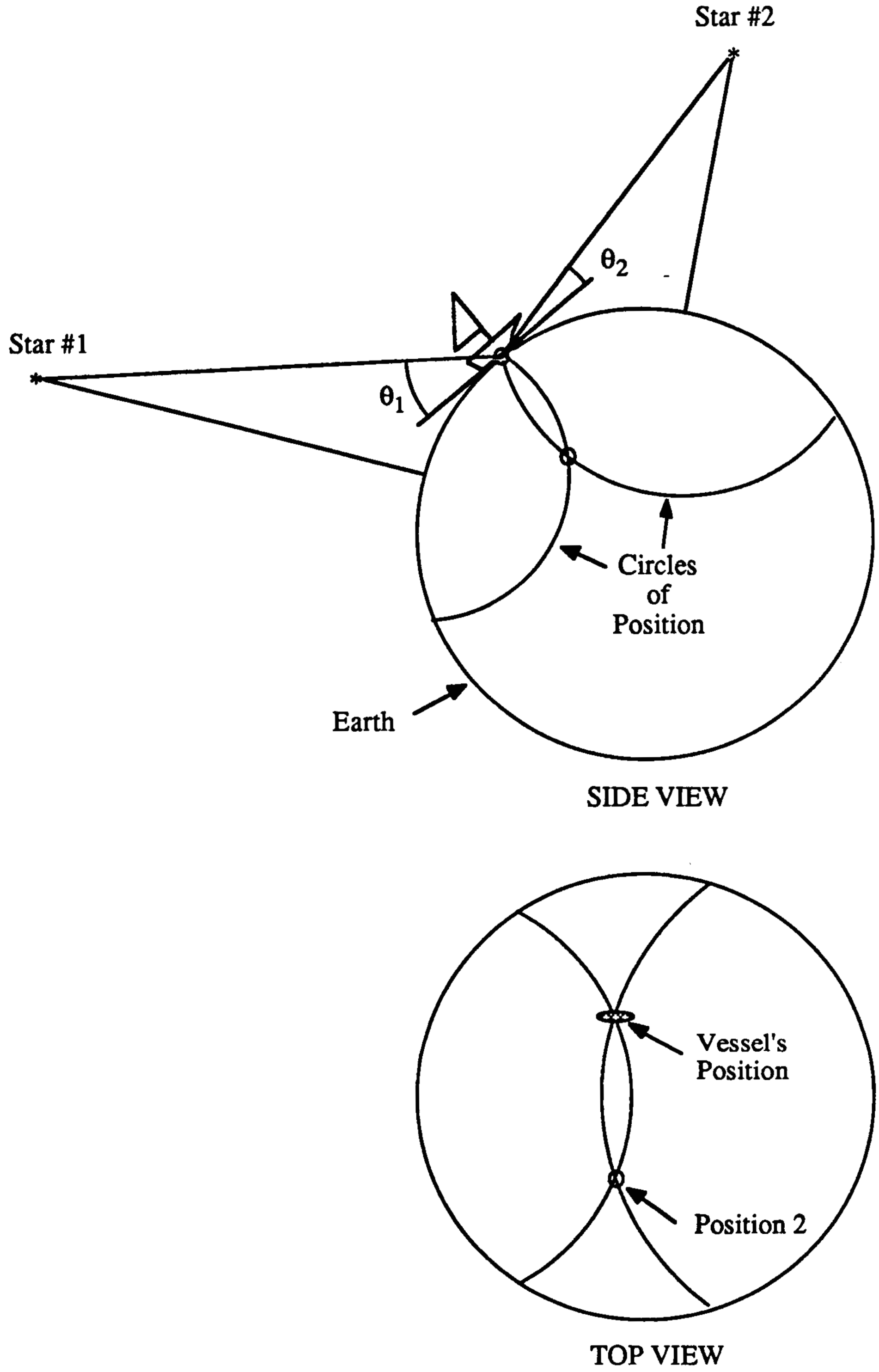


Figure 2: TWO-STAR METHOD OF CELESTIAL NAVIGATION

number of degrees, minutes, and seconds a celestial body is above the navigator's **horizon** and is measured using a marine sextant. A bubble sextant may be used to compensate for terrestrial irregularities and account for the differences between the navigator's apparent horizon and the true horizon.[33] The Nautical Almanac or the Air Almanac tabulates the declinations and Greenwich Hour Angles for the Sun as well as certain stars and planets. With the altitude information from the sextant and the known GMT and date, the almanac will yield the radius of a circle of position and the observer can graphically derive his position. Data from one pair of star sights yield two possible positions, usually widely separated and easily distinguished. Data from a second pair of star sights will accurately determine the observer's exact location.

As an alternative to graphical solutions, the two-star celestial problem can be solved in closed analytical form. Two circles of position are defined by the observed altitudes of two stars, the time of observation, and information from either the Air Almanac or Nautical Almanac. Multiple sets of simultaneous equations can be solved to yield the two intersections of the circles of position.[30] The observer's location is one of these two intersections. If the navigator cannot identify his location between the two points, a second pair of star sights will fix his exact position. This method is readily adaptable to a hand-held, programmable calculator.[16]

APPLICATION OF CELESTIAL TECHNIQUES TO LUNAR NAVIGATION

Two aspects affect the transfer of a celestial navigation technique from the Earth to the Moon: 1) a selenographic aspect relating to the physical factors of the lunar environment, and 2) an astronomical aspect concerning the unfamiliar pattern and behavior of celestial bodies in the lunar sky.[14]

Selenographic Aspect

The lunar sphere is suitably furnished with a spherical coordinate system similar to the Earth's so that position may be defined in terms of lunar latitude and lunar longitude. The lunar north and south poles are located at the extremities of the rotational axis, and the lunar equator is a **great circle** equidistant from the poles. Lunar charts delineate the lunar **prime meridian** and its intersection with the lunar equator at the **mean center** of the Moon at **mean libration** (when all four **limbs** are equally exposed).[14]

The accuracy of a position determined from celestial observations depends on the accuracy with which observations can be taken from the lunar surface. Instruments which refer to a natural horizontal reference will be inaccurate on the Moon due to the absence of water areas to serve as an elevation datum such as sea level.[14] Observations taken with a bubble sextant are subject to error due to gravity anomalies arising from the Moon's low value of gravity and the presence of various mass concentrations. The celestial altitudes measured will require corrections for **parallax** (the change in direction of an object as seen from two different positions) and **semi-diameter** (the error caused by the inability to locate the exact center of a celestial body when using it as a celestial reference).[33] Refraction corrections will also be necessary as observations will be taken from the interior of a vehicle or through a visor.[14]

Astronomical Aspect

To an observer in the lunar world, the Moon appears to be stationary at the center of the universe and the visible celestial bodies to be on the inner side of an infinite extension of the Moon's sphere. The position of a celestial body may be defined by its celestial latitude or declination and its celestial longitude or hour angle.[14]

The Moon's north **celestial pole** is inclined to the **pole of the ecliptic** 1.5 degrees so that the Sun is always within 1.5 degrees of the lunar celestial equator. The interval between two successive transits of the Sun over a lunar observer's meridian is 29 days, 12 hours, 44 minutes, and 3.2 seconds or approximately 708.7 hours. Thus, the **diurnal** motion of the Sun is about 0.508 degrees per hour.[14]

The interval between two successive transits of the vernal equinox over a lunar observer's meridian is 27.321661 days such that the diurnal motion of a star is 0.5305 degrees per hour.[14]

The Moon's rotation on its axis and revolution in its orbit around the Earth take place in the same direction and in the same period, so that it always keeps the same side directed toward the Earth. On the far side of the Moon, the Earth is not visible. On the near side of the Moon, the Earth appears at or near the mean center. The visible Earth has no rising or setting except for observer's near the extremities of the limbs. However, the Earth has an apparent periodic north-south, east-west oscillation which for navigation purposes may be translated as a change in declination and hour angle. In effect, at any instant of time, the Earth's declination and hour angle are known and are correction factors for locating the mean center of the Moon, the lunar prime meridian and the observer's longitude.[14]

PROPOSED ADAPTIONS OF CELESTIAL TECHNIQUES FOR THE MOON

One method of lunar navigation suggests using the change in location of the Earth and Sun in the lunar sky due to the Moon's physical libration. In the Earth-Moon system, rotation and revolution are real motions of the bodies, while librations are apparent oscillations arising from the geometry of the system.[33] To an observer on the Moon, terrestrial librations appear as changes in the Earth's declination and hour angle. Librations in latitude result from the 6.5 degree inclination of the Moon's equator to the plane of its orbit. As the Moon revolves in its orbit, the polar axis remains parallel to itself and the Moon oscillates between zero degrees and a maximum declination of 6.5 degrees north and south. Librations in longitude are due to the eccentricity of the lunar orbit. As the orbital velocity exceeds the rate of rotation, the Earth attains a maximum value in hour angle of about 7.75 degrees east and west. Because the Moon's north celestial pole is inclined to the pole of the ecliptic 1.5 degrees, the Sun is always within 1.5 degrees of the lunar celestial equator. The American Ephemeris tabulates the daily selenographic latitudes (declinations) and longitudes (hour angles) of the Earth and the Sun as seen on the Moon. One of the variables for entering the tables is the **age of the Moon**. The Moon's age expresses its position in relation to the Earth and the Sun and can be estimated from the apparent phase of the Earth as seen from the Moon.[14] With this information, the navigator can estimate his position using a technique similar to that on Earth.

As an alternative to the sight reduction tables, a **celestial coordinator** may be used to indicate the computed altitude and **azimuth**. A celestial coordinator is a manual computer for solving spherical triangles and consists of two spherical grids, one in the plane of the equinoctial superimposed on another in the plane of the horizon. The computed altitude and azimuth are found by plotting the local hour angle and declination of the celestial body. Assuming the Earth and the Sun to be on the lunar celestial equator, and the Earth on the lunar prime meridian, the observer can find his "assumed" latitude and longitude. A **libration coordinator** may then be used to correct this assumed position to find an estimated **selenocentric** position. The libration coordinator is a set of templates and indices set to the longitudes of the **ascending node, perigee** and the Sun in order to compose a graphic aspect of the occurring phenomena in the Moon-Earth-Sun system. That is, the libration coordinator estimates the error caused by assuming the Earth and the Sun to be on the lunar celestial equator and the Earth to be on the lunar prime meridian. The "assumed" latitude and longitude can incorporate errors which range from zero to 321.9 kilometers.[14] This method of lunar navigation is attractive as it uses already available information and would be easy to implement. However, as already mentioned, the Earth is not visible from the far side of the Moon and the Sun is visible only for a 14.5 day period. Therefore, this method is only applicable at certain places and times of the lunar day.

When the Earth and Sun are not simultaneously visible, the observer's position can be figured by taking observations of a single body at two identified times. When neither the Sun nor the Earth are visible, the observer must use two known stars in order to fix his location.[33] The nearest bright star to the lunar north celestial pole is Zeta Draconis, a 3.6 magnitude star about 5.5 degrees from the pole. Delta Dorado, a fourth magnitude star, is approximately 2 degrees from the south celestial pole. Polaris is within 22 degrees of the north celestial pole, and Betelgeuse, whose terrestrial declination is N 7°23', is close to the lunar celestial equator.[14] Use of these stars will require tabulated data similar to the Nautical Almanac or Air Almanac used in navigation on Earth. This would mean charting the altitudes of certain stars as seen from the Moon at a known time and date, and then defining the radii of the circles of position using the curvature of the Moon. Because the diurnal motion of a star as seen from the Moon is much slower than that of a star observed from Earth (0.5305 degrees per hour), the clock used to indicate the lunar meridian time (compared to Greenwich Mean Time) must be extremely precise.

In order to use any celestial navigating technique, the observer is required to manipulate a sextant or some sort of instrument to measure the altitude of the celestial body. On the Moon, physical movement by the astronauts is constrained and the design team suggests attaching the instrument to the astronaut's helmet to make it readily available. Similarly, any analytical solver used to provide a position fix should require little input from the astronaut so as to make it simple for him to use. Finally, some method to define the true horizon must be designed so that the altitudes of the stars can be measured as accurately as possible.

The primary advantage to a celestial navigation method is its independence. A navigator with a sextant and the necessary tabulated data can find his position with minimal difficulty and some accuracy. Also, the cost associated with this method of navigation is minimal, resulting primarily from the cost to derive the tabular data and the cost of the sextant used. However, celestial navigation has some disadvantages; these include:

1. The lunar observer will not be able to readily manipulate a sextant, read tables of data, or work hand-held computers.

2. Due to the lack of an elevation datum such as sea level, it will difficult to identify the **celestial horizon**. Bubble sextants cannot be used to create an artificial horizon because of the inhomogeneous gravitational field on the Moon.

SATELLITE NAVIGATION

The design team considered four satellite navigation systems, each with different operating frequencies and/or principles, for adaption to the lunar surface. These were Transit, Navstar, Navsat, and Geostar.

Satellite transmissions provide two basic measurements: position (range) and line-of-sight velocity (range-rate). Range is measured from the time it takes a carrier signal to travel from the satellite to an observer, and range-rate is determined from the **Doppler** shift in frequency of the received signals. These measurements are used to derive navigational information either by observing a single satellite over a time interval as it passes across the hemisphere (Transit), or by making measurements to several satellites that are in view simultaneously (Navstar, Navsat, Geostar).

In order to use the range and range-rate to provide latitudes and longitudes, the user must have information about the positions and velocities of the satellites as a function of time. This **ephemeris** data is transmitted to the user-receiver by phase modulating the carrier signals used for Doppler measurements.[2]

Ground tracking stations at precisely known positions use the navigational measurements (range and range-rate), combined with data on atmospheric conditions, to calculate satellite **ephemerides** and clock offsets. This data is communicated back to the satellites via uplink stations. Because uplink communications may be infrequent, satellites must be equipped with clocks of sufficient accuracy to ensure precise downlink transmissions between updates.[2]

TRANSIT

Transit is the only fully operational and generally available satellite navigation system. It has been operated by the U.S. Navy since 1959 and is accessed by over 40,000 users, 90% of them civilian. Transit consists of six operational satellites in 1,075 kilometer orbits with one in-orbit spare. Each satellite transmits carrier frequencies of 150 and 400 megahertz.[2]

Transit Navigational Algorithm

The navigational algorithm for this system is formed by extracting information from a phase-locked loop. The user-receiver monitors the total number of carrier cycles received from the satellite over a certain interval. This essentially is the integration of line-of-sight velocity (range-rate) over the time interval to give the corresponding change in range (Δr) to the satellite. Range-rate is determined from Doppler measurements of the frequency shift of the received signal. These measurements actually give a fractional frequency shift of:

$$\Delta v/v = -d/dt \{\int V(1)^{-1} dl\}$$

This is the rate of change of the transit time from the satellite to the observer, where V(1) is the propagation phase velocity of the carrier signal.[2]

The phase-locked loop can track the received signal to a small fraction of a wavelength, giving an extremely accurate Δr measurement. But since this measurement only yields the change in range (delta range), rather than the absolute range at a given instant, an iterative search of position must be undertaken until agreement is obtained with the measurements.[2]

Accuracy

Transit is able to provide a single position fix approximately every 90 minutes.[27] Due to ionospheric and tropospheric refraction, the accuracy of this fix depends on the user's knowledge of velocity and height above the reference spheroid.[2]

Transit has four ground stations located in the U.S. that provide uplink information on satellite orbital parameters every 12 hours. Two dimensional (latitude and longitude) root-mean-square (RMS) radial accuracy is quoted at 25 meters (approximately 82 feet), but significant error can result from inaccurate velocity measurements.[2] A relatively recent improvement applies the technique of translocation to give quoted RMS radial accuracies on dynamic fixes of 12 meters (approximately 40 feet).[27]

Satellite fix translocation involves a control site at a known location and a remote site at an unknown location. Range-rate measurements are collected at both sites from the same satellite. The measurements from the control site are then used to compute correction terms to the satellite system instead of being used to solve for location. These correction terms are then used with the measurements at the remote site to solve for the remote site's location. The translocated fixes are more accurate than fixes computed without the benefit of control site corrections to satellite orbital parameters. Static fix RMS accuracy improves from 13 to 5 meters, with accuracy on dynamic fixes stated above.[27]

NAVSTAR

The success of Transit spurred the Department of Defense to examine systems that would provide increased capability to high dynamic users (i.e., aircraft). This led to the creation of the Navstar Global Positioning System (GPS).[2]

As currently planned, the complete Navstar system will consist of 18 primary satellites with three in-orbit spares. The satellites will be deployed in six circular orbital planes of 20,183 kilometer radii. The planes are 60 degrees apart longitudinally with an inclination to the **equatorial plane** of 55 degrees. Three satellites will be deployed in each plane with a 120 degree spacing between them. Between planes, satellites will be phased 40 degrees apart (i.e., a satellite in one plane will have a satellite 40 degrees to the North of it in the plane directly to the East). When fully operational, Navstar will be able to provide continuous, global, three-dimensional positioning coverage that is repeatable and precise. Full operational capability is scheduled for the 1990's.[10]

The Navstar GPS control segment performs the tracking, computation, updating, and monitoring functions needed to control all satellites in the system on a day-to-day basis. This involves nominally five monitor stations, a master control station, and three upload stations. The control segment is able to provide uplink information (navigation and timing data) at least once a day.[10]

Each satellite transmits two carrier frequencies centered on 1,575.42 and 1,227.60 megahertz. These signals are exact multiples of the satellite clock frequency (10.23 megahertz) and convey range information via modulations that are locked in time to the atomic standards.[10] To extract the signal and recover the necessary navigation data, the user receiver must be able to cross-correlate all GPS satellite signals present, as modulations are unique to each satellite. This type of operation uses spectral division made possible by modulating the carrier signals with pseudorandom noise (PRN) codes. Two PRN codes are transmitted by each satellite: the standard positioning service (SPS) and the precise positioning service (PPS). The SPS is used to aid acquisition of the satellite signals and provide course navigation, while the PPS, with a ten times higher modulation rate, is used for full navigational accuracy.[2]

PRN codes also form the basis of the Navstar navigational algorithm. A carrier signal is multiplied by a seemingly random sequence of +1's and -1's of duration $1/b_r$, where b_r is the bit-rate of the code in units of inverse seconds. If the sequence is agreed rather than being truly random, the arrival of code states along the line of sight from the satellite to the observer can be timed to derive range information. Effectively what is measured is:

$$\Delta t = \int V_g(1)^{-1}\, dl,$$

where $V_g(1)$ is the group velocity of the intervening medium. To convert the measurement of Δt to a true range value, it is necessary to include the effects of the intervening media, which reduce $V_g(1)$ below the speed of light in a vacuo.[2]

Navstar Navigational Algorithm

Unlike the Transit system, Navstar GPS will provide continuous position information. By measuring the Doppler shifts of the radio frequency carriers, a user can calculate the range-rate to a particular satellite. Once again, the Doppler measurements yield a fractional frequency shift of

$$\Delta v/v = -d/dt\{ \int V(1)\, dl\},$$

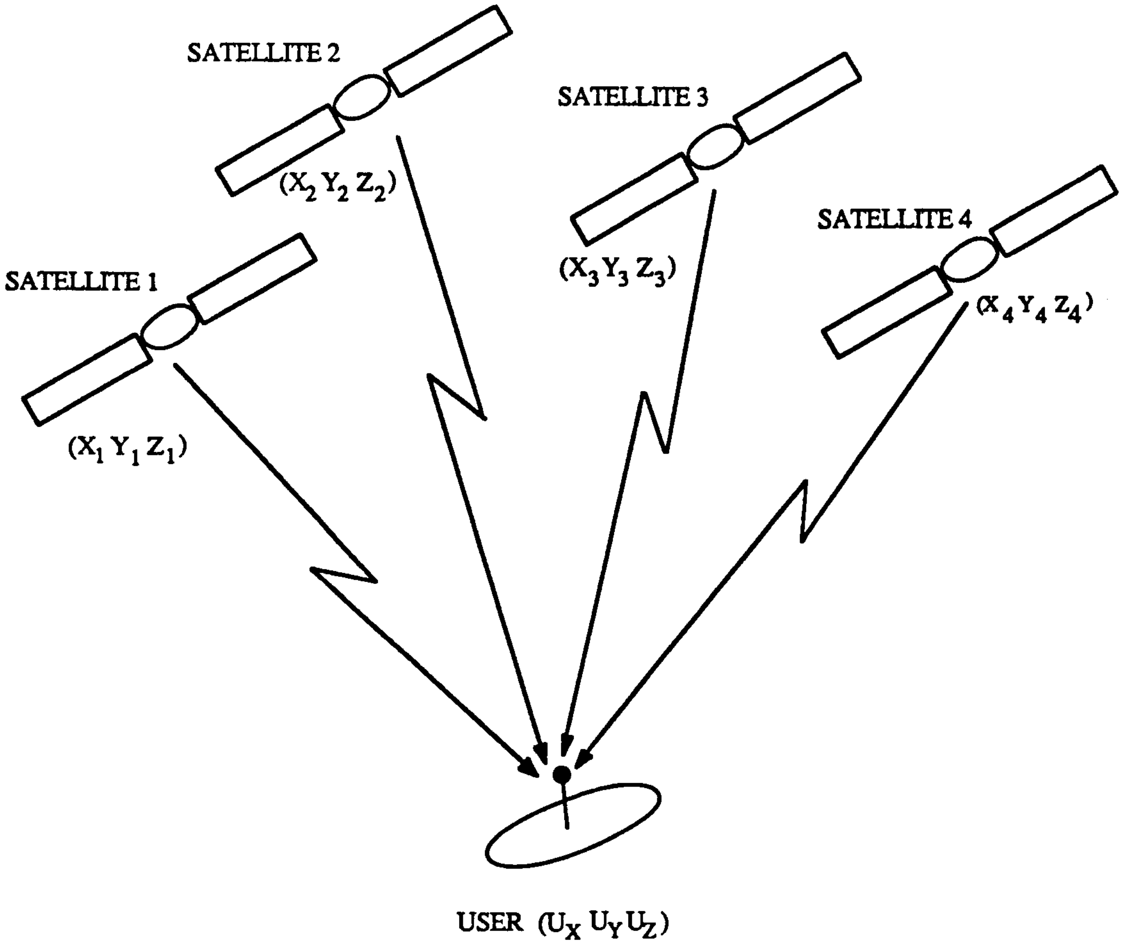
where V(1) in this case is the group velocity of the intervening medium. In a Navstar receiver, range-rate is measured using a phase-locked loop designed to lock a voltage controlled oscillator to one of the phases of the underlying signal. The range-rate is determined by the frequency at which the loop locks.[2]

In addition, by monitoring four satellites, the observer can determine his three-dimensional position (latitude, longitude, and altitude) and apply corrections to his clock which does not have the inherent stability of the satellite atomic clocks. If the observer is constrained to the Earth's surface, he can determine his two-dimensional position using three satellites. The procedure is as follows:

1. The user receiver computes four pseudo-range values from time signals (Δt's) transmitted by the four satellites. The pseudo-range differs from the true range due to the previously mentioned effects.

2. The receiver then computes position coordinates by solving four equations with four unknowns.

This process is illustrated in Figure 3.[2]



Time signals transmitted <u>by satellites</u>	<u>Pseudo-range values</u>
Δt_1	$R_1 = c\Delta t_1$
Δt_2	$R_2 = c\Delta t_2$
Δt_3	$R_3 = c\Delta t_3$
Δt_4	$R_4 = c\Delta t_4$

$$(X_i - U_x)^2 + (Y_i - U_y)^2 + (Z_i - U_z)^2 = \{R_i - c[\Delta t_{Ai} - (\Delta t_u - \Delta t_{Si})]\}^2$$

c	=	speed of light in a vacuo
Δt_{Ai}	=	propagation and relativity effects (communicated downlink to receiver by satellite)
Δt_u	=	user's clock offset from GPS time (unknown)
Δt_{Si}	=	satellite's clock offset from GPS time (communicated downlink to receiver by satellite)

Figure 3: NAVSTAR NAVIGATIONAL ALGORITHM

Accuracy

The Navstar position accuracy is defined by the area (or volume) formed by the intersection of the three (or four) circles whose equations are given in Figure 3. Two-dimensional system accuracy using the PPS has been quoted as 18 meters RMS horizontally and 15 meters RMS vertically. The accuracy available to civil users with the SPS is set at 100 meters **spherical error probability** (SEP).[2]

The technique of translocation may also be applied to the Navstar system (referred to as differential GPS) to give accuracies using the SPS that are comparable to those using the PPS. However, a data link is necessary to transmit the differential correction, and the user and static receiver are constrained to use the same satellite set.[27]

NAVSAT

Restrictions on Navstar civil operations sparked proposals for satellite navigation systems specifically for civilian users. Navsat, developed in studies for the European Space Agency, is perhaps the most notable of these proposals. The goal of Navsat is to minimize user equipment and the space segment by simplifying the signal format. The trade-off is ground station complexity.[2]

The proposed Navsat concept consists of 18 satellites -- 12 in highly eccentric orbits (HEO) equally shared between Northern and Southern hemispheres and 6 navigation packages on board **geosynchronous** (GEO) host satellites.[5] The satellites will operate on link frequencies protected by international agreement among the ground control segment that is to be distributed among cooperating countries. In this way, constant uplink transmissions can be maintained. Satellites can be designed to act simply as transponders by using a Time Division Multiple Access (TDMA) signal structure. This will allow navigational messages to merely be relayed through the satellites by the ground control segment, thereby simplifying the space segment.[2]

The navigational algorithm is identical to Navstar, with three-dimensional position fixes possible by monitoring four satellites that are in view simultaneously. Since jamming protection is not needed, a simpler signal format (TDMA) can be employed to make user equipment less complex. TDMA may contain PRN codes, but the modulations need not differ from satellite to satellite. Hence, the user receiver does not need software to choose a subset from the satellites in view that gives the most favorable geometry for navigational calculations.[2]

The proposed control segment consists of nominally five ground stations that are responsible for determining satellite ephemeris data and generating uplink transmissions. One requirement of this segment is that each satellite is visible from at least one ground station at all times.[2] Three-dimensional position error with the Navsat system is quoted at 12.5 meters spherical error probability (SEP).[5]

GEOSTAR

Dr. Gerald K. O'Neill, a physics professor at Princeton University, has designed the Geostar Satellite System,[31] a commercial network that provides radiodetermination, radiolocation, and radionavigation from the same set of user equipment. Radiodetermination is defined by the Federal Communications

Commission (FCC) as "the determination of position, or obtaining information relating to position, by means of the propagation of radiowaves".[23] Elements of the Geostar system include a ground control facility, two or more geosynchronous relay satellites, and a user transceiver.

The Geostar system consists of four communication links, two Earth-to-space and two space-to-Earth. The ground control facility includes three computers, only one of which operates the system at a given time. The remaining computers are used as stand-bys. One duplicates all computations in case of primary computer failure, while the other is used for new program development. The primary computer sends a general interrogation signal at the rate of 100 times per second through one of the relay satellites. If a user transceiver wants to respond, it reads the interrogation and sends it information. Geostar uses pulse radio transmissions that allow the entire message to be sent in .6 seconds.[31]

The transceivers feature a liquid crystal display (LCD) readout with alphanumeric keypads to enter messages. To keep messages separate, each transceiver has a unique digital identification code, or "fingerprint," to be included in each message.[31] By measuring the time it takes for the user to respond to the interrogation signal, the ground computer can accurately determine the transceiver's position. This roundtrip transit time is monitored by delay (phase) locking a local replica of the user code with the received code and measuring the associated time delay, Δt. Multiplying Δt by the speed of light gives the (pseudo) roundtrip range from the ground facility to the user transceiver. The true range is found by subtracting out bias and random error sources.[23]

Geostar Navigational Algorithm

The Geostar algorithm used to calculate user position is illustrated in Figure 4. The user's response to the ground facility interrogation signal passes through two satellite relays, effectively defining two round-trip ranges to the transceiver. These ranges plus information on the user's altitude give three equations to be solved simultaneously for the user's position.[23]

1. $|R_1| + |R_2| + |R_2| + |R_1| = r_1 - c(dt_{bias1}) - c(dt_{random1})$
2. $|R_1| + |R_2| + |R_3| + |R_4| = r_2 - c(dt_{bias2}) - c(dt_{random2})$
3. $|R_u| = (r_e + h)$,

where R_1, R_2, R_3, R_4 = true range vectors defined in Figure 4

R_u = user's position vector from the center of the Earth

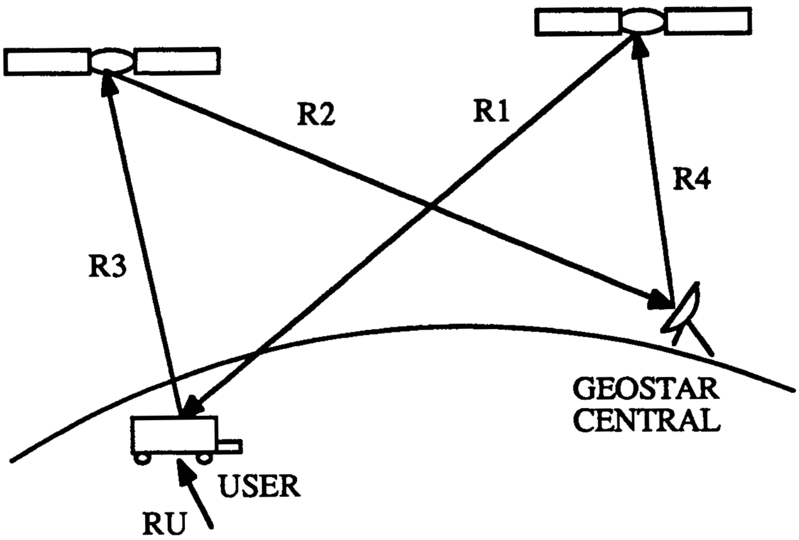
$r_e + h$ = user's distance from the center of the Earth

r_e = radius of prime vertical of reference ellipsoid

h = user's altitude

Differential Operation and Accuracy

Differential operation of the Geostar System eliminates many sources of bias error from range measurements. Bias errors include satellite ephemeris errors, ionospheric and tropospheric refraction, and delays through system electronics. This is accomplished by the use of "benchmark" transceivers at known locations. The benchmark corrections can be applied both to range measurements and to final positioning solutions.[23]



$$r = R + c(dt)_{bias} + c(dt)_{random}$$

r	= measured round trip range (c(dt)meas)
R	= true round trip range
dt_{bias}	= bias timing errors (atmospheric refraction, ground delay, multipath)
dt_{random}	= random timing errors (transceiver noise)
c	= speed of light

Figure 4: GEOSTAR NAVIGATIONAL ALGORITHM

The correction as applied to range measurements involves calculating the true ranges to a benchmark using the known benchmark, satellite, and ground facility positions. The calculated roundtrip range is subtracted from the measured range to yield the range bias valid for that area. This range bias is then used to correct the measured ranges of user transceivers in the vicinity before the positioning calculation is performed.[23]

Applying benchmark corrections to position solutions involves using the Geostar algorithm (see Figure 4) to calculate the benchmark position from uncorrected range measurements. This estimated position is then compared with the known benchmark position, and the difference is used to correct positioning solutions of users in the area.[23]

Assuming perfect knowledge of user altitude, Geostar two-dimensional positioning accuracy is quoted as 5 to 7 meters. Three-dimensional accuracy is influenced by errors in the third dimension (i.e., digital terrain map and altimeter errors) and is quoted as 35 to 60 meters.[23]

MEASUREMENT CORRECTIONS

The error sources that affect range calculations are atmospheric delays, **special and general relativity** effects, satellite ephemeris errors, ground delays through system electronics, transceiver noise, multipath, and altitude errors.

Atmospheric Delays

The ionosphere and troposphere have a delaying effect on satellite transmissions that causes the phase and group velocities of radio signals to be significantly different from those in a vacuo. Hence, raw navigational measurements must be corrected for these effects before being used in the navigational algorithm.

It can be shown that ionospheric delay can be characterized by the surface density of electrons along the line of sight from the satellite to the observer. In the Transit system, the Doppler shift of a radio frequency carrier is monitored for range-rate measurements. The range-rate is then effectively integrated to give the associated change in range. Since the fractional frequency shift ($\Delta v/v$) is equal to the rate of change of signal transit time from the satellite to the observer, Δt is proportional to $1/v^2$. This makes it possible to correct for ionospheric delay by making range-rate measurements at two carrier frequencies.[2]

Navstar corrects for this delay by transmitting model parameters of the ionosphere to the observer in the navigational message. By using this technique, as well as making Δt measurements at two frequencies, Navstar is able to give the most accurate navigational service.[2]

The troposphere, unlike the ionosphere, is a nondispersive medium of radio frequencies. Because of this, the tropospheric delay cannot be corrected by multiple frequency observations, and it becomes necessary to model the effect. The medium can be characterized by a frequency-independent refractive index, n(1). The tropospheric delay can then by expressed as:

$$\Delta t = c^{-1} \int n(1)\, dl,$$

where c is the speed of light in a vacuo. The simplest models of this delaying effect usually assume a height-dependent refractive index.[2]

Under extreme meteorological conditions, the errors that result from the use of such a standard atmosphere at low elevation angles can be large. It then becomes necessary to apply an additional correction to range-rate measurements if high accuracy is required. In the Navstar system, it is best not to use transit-time measurements from satellites below about five degrees elevation when precise navigational data is needed.[2]

Special and General Relativity Effects

For a system that measures satellite range from signal transit time and that uses accurate timing standards in the satellites (i.e., atomic clocks), the effects of special and general relativity must also be considered. Special relativity dominates satellites in low-Earth orbit. This effect causes the satellite clock to appear to run slowly to an observer on the surface of the Earth.[2]

On the other hand, satellites in high-Earth orbit are dominated by the theory of general relativity. This theory dictates that, because the satellites are at a higher gravitational potential than the observer, satellite clocks will appear to run fast. General relativity effects must also be considered for precise navigational fixes. Consider the Navstar satellites for example, in which the effect of general relativity dominates. To correct for this effect, satellite clocks are built to run deliberately slow on the Earth's surface.[2]

Satellite Ephemeris Errors and Ground Delays

Other error sources that affect the range calculations in systems using transit time measurements are satellite ephemeris errors (slight deviations of the satellite from its orbit) and ground delay through system electronics.[23] These errors may be eliminated through differential operation of the systems. As mentioned earlier, the Transit, Navstar, and Navsat systems accomplish differential operation by applying the technique of translocation, while Geostar uses benchmark transceivers at known locations.

Transceiver Noise, Multipath, and Altitude Errors

Further considerations for the Geostar system are transceiver noise, multipath and altitude errors. Transceiver noise causes a time delay given by:

$$dt = T_c \{(3B_L/2B_{IF})[(33/80P_i) + (1/2P_i^2)]\}^{1/2}$$

where T_c = chip duration

B_L = tracking loop bandwidth

B_{IF} = post-correlator IF loop bandwidth

$P_i = C/N_oB_{IF}$

C/N_o = signal-to-noise power density ratio

Transceiver noise has two opportunities to affect the range measurement. First, when the user transceiver is tracking the outbound interrogation from the ground computer, and second when the ground computer measures the roundtrip signal transit time.[23]

Multipath refers to the arrival of multiple signals from the same source at slightly different times. There are two sources of multipath error. First, ground reflections occur when a signal is traveling to the user at low elevation angles. Two aspects of the Geostar system compensate for this delay: geosynchronous satellites ensure relatively large elevation angles for most users and the spread spectrum transceiver effectively overcomes multipath signals delayed more than a chip width. The second source of multipath error, diffuse multipath, occurs with the addition of many slightly delayed signals caused by interactions between the vehicle body and the antenna. This source of error is not well characterized but should not contribute a range error of more than one meter.[23]

The Geostar system uses two range measurements and a digital terrain elevation map to find the three-dimensional position of a user constrained to the ground. Airborne users provide altimeter information to the ground facility in place of the terrain elevation map. Altitude errors from altimeters and digital terrain maps influence the absolute positioning accuracy.[23]

ADVANTAGES AND DISADVANTAGES OF SATELLITE NAVIGATION

The design team has identified the following advantages and disadvantages of adapting satellite navigation to the lunar surface.

Advantages

1. With proper user equipment, the satellite system can be operated by an astronaut within the physical limitations of full space gear.

2. Astronauts need not have physical siting of the Earth or Sun to utilize the system.

3. With appropriate coverage, the system would be operational over the entire lunar surface.

4. The system is extremely accurate, providing position fixes well within sight distance. This accuracy is enhanced on the lunar surface due to the lack of an atmosphere to delay satellite signals.

Disadvantages

1. The cost associated with transport, set-up, and maintenance of satellite ground control facilities on the lunar surface would be significant, if not prohibitive.

2. The orbital mechanics involved in establishing a satellite orbit around the Moon are complicated by the small mass and diameter of the Moon, as well as the gravitational pull of the Earth.

3. The satellite system would not account for navigation in a strict "lifeboat" situation. Although the astronaut would not need to communicate with a lunar base facility to use the system, he would require a vehicle to carry user equipment. Efforts are progressing to streamline this equipment and make it physically manageable.

INERTIAL NAVIGATION

Inertial navigation systems are self-contained, non-radiating, non-jammable and sufficiently accurate means of **dead-reckoning** guidance. Inertial systems are based on the constancy of momentum, the existence of gravity, and the accurate measurement of time. The standard configuration of an inertial navigation mechanism consists of three single-degree-of-freedom gyroscopes in conjunction with three single-axis accelerometers mounted so that their input axes form an orthogonal triad. The gyroscopes prescribe an inertial reference frame, while the accelerometers tie an object to Earth via gravitational mass attraction. Together, these components measure the vehicle's motions about and along three orthogonal axes in order to keep track of its precise position, angularity, and linearity. As the vehicle travels, the system measures and logs relative position changes and then calculates an updated vehicle location.[18]

One of the major advantages of an inertial navigation system is its self-independence. A user need not depend on any outside source to plot his own course. The one major drawback in the purely self-contained system is the inherent random walk error associated with its operation, especially on land.

This error is due to the Earth's rotation within the inertial reference frame and can be corrected by calibrating the inertial instrument. Directional calibrations are made by using the Earth's magnetic field to define north, or the mass gravitational attraction to define the local vertical. In addition, much of the error can be corrected by cross-referencing the inertial findings with those of some other navigation technique. A one-star stellar reference may be used for correction of heading misalignment, or a two-star fix will permit determination and comparison of position. Also, radio-signal comparison, whether by beacon or satellite, will allow update and comparison of all reference directions.[18]

Some of the main advantages of one or more of these cross-referenced systems are as follows[3]:

1. Reaction time can be reduced by giving the initial parameters using an external reference.

2. If the external system fails, the inertial mechanism will still maintain sufficient accuracy until the signal is re-acquired.

3. If only a partial or degraded signal is available, it can still prove useful in determining position.

4. The inertial system can be used to aim the antenna in order to reduce acquisition time of the external reference and control the receiver band width.

Certain considerations are involved in adapting inertial navigation to the lunar surface. Although the system has the significant advantages of being self-contained and relatively inexpensive, it also has some shortcomings. Since gyroscopic positioning is based on the existence of gravity and the constancy of momentum spin of the reference body (i.e., the Earth or Moon), the system has serious drawbacks for lunar application. The Moon has roughly one-sixth the gravity of the Earth and only about one-twenty-eighth the rate of spin, so a gyroscope will not function as well or as accurately as it does on the Earth. Also, the ruggedness of the Moon's terrain will effect the operation of this sensitive instrument.

RADIO-BEACON NAVIGATION

Ground-based radio beacon navigation can provide fairly accurate, automated global coverage for system users. Currently, several successful beacon navigation systems exist for Earth application. Each system uses different principles, equipment, and transmission signals.

PULSE MATCHING SYSTEMS

Pulse radio-beacon systems measure either the arrival times of pulse signals from the beacons or the difference in arrival times of pulses from two or more beacons. This information is used to derive distances or differences of distances between the mobile unit and the corresponding beacons. An example of this type of radio-beacon system is LORAN.

One of the first fully developed radio-location methods in operation was LORAN, an acronym for long-range navigation. The current version, LORAN-C, uses low-frequency (100 kilohertz) transmissions to provide synchronized pulse signals at a common repetition rate called a chain. One station is designated the master and the others are designated secondaries. In the original and conventional mode, a LORAN-C user's receiver measures the time difference (TD) between the master station and a secondary station's X-signal. This defines a hyperbolic line of position, TDX. Measurement between the master signal and another secondary Y defines a second line, TDY. The intersection of these lines defines the receiver location. A third secondary Z provides coverage for other receiver locations where one of the other secondaries does not provide good signals, closely spaced hyperbolas, or good crossing angles. There may be up to five secondaries synchronized to one master where geography is less favorable.[8]

For conventional LORAN-C operation, the ground-wave signal is utilized for highest accuracy. Measurements are made at the end of the third cycle to prevent contamination by the sky wave, which travels a longer path. To eliminate mutual interference between the stations of a chain, signals are transmitted on a time-shared basis, with timing chosen to provide guard regions against overlap anywhere in the system. To achieve higher average power, a group of eight pulses is sent from each secondary station, with 1,000 milliseconds between pulses. The duration of the pulse pattern is known as the Group Repetition Interval (GRI). These GRI's are varied to distinguish chains and to minimize interference between chains.[8]

To obtain highest accuracy in LORAN-C, it has been necessary to consider two main factors. These are the correction for primary phase propagation through the atmosphere, and the correction in the amount (in microseconds) by which the secondary phase signal is delayed by propagation over terrain of various conductivities and profiles.[8]

For application to the lunar surface, LORAN-C has certain advantages and disadvantages. The major drawbacks of this system are in the potential cost, and the difficulty in set-up and maintenance of the ground bases. Master stations can be large, housing up to 64 half-cycle generator units, each weighing approximately 25 kilograms. Furthermore, efficient transmitter antennae for high-power stations are on the order of 190 meters (625 feet) to 412 meters (1,350 feet).[8]

The advantages associated with the implementation of a LORAN-C type system are:

1. The system would be simple to use.
2. It would have increased accuracy due to the lack of a lunar atmosphere.
3. It would not need to account for the physical abnormalities of the Moon (i.e., non-spheroidal geometry, and mass concentrations).

PHASE COMPARISON SYSTEMS

Phase-comparison radio-beacon systems measure the phase difference in signals from two or more beacons to derive position information. Accurate positioning requires that signal waves propagate such that they follow the surface of the Earth. An example of a phase-comparison system is OMEGA.

OMEGA is a very long-range ground-based radio navigation system which provides worldwide, continuous coverage. This system consists of eight ground-based transmitting stations which use phase comparisons of very-low-frequency continuous hyperbolic wave signals in the 10 to 14 kilohertz band.[28] Each station radiates omni-directional, time-multiplexed transmissions of 10.2, 11.05, 11.33, 13.6 kilohertz and one additional frequency unique to each station. These corresponding patterns allow the user to identify the transmitters that he is able to receive.[9]

Each station's transmissions are synchronized in phase through the use of CESIUM beam frequency standards at each site. The measurements of phase difference from three or more transmitters provide position information to within approximately 4 nautical miles 95% of the time, depending on the geographic location of the user, the station pair selected, and the accuracy of the propagation corrections in use. The OMEGA signals propagate in the Earth ionosphere and the waveguides are formed between the D-region of the ionosphere and the Earth's surface.[9]

OMEGA provides a worldwide, all-weather radio navigation system with phenomenally low operating and maintenance costs for Earth use. For lunar application, these costs would be over-shadowed by the difficulty of implementation and maintenance of the lunar beacons. Furthermore, due to the lack of an ionosphere to provide waveguides, the type of OMEGA transmission signals would need to be modified to direct-propagation signals. Such signal adaption may effectively increase the need for a larger number of bases than would otherwise be required. This could potentially spoil OMEGA's primary advantage -- the need for few base stations (eight).

SPREAD-SPECTRUM SYSTEMS

Spread-spectrum radio-beacon systems use a carrier signal centered on a particular frequency and modulated with a pseudorandom noise (PRN) code as the basis of their algorithm. The mobile units time the arrival of code states along the signal path to determine distances or differences of distances between the mobile and corresponding beacons. An example of this type of system is GEOLOC.

GEOLOC is a radiolocation system which uses spread spectrum transmission in the high frequency 1.6 to 2.3 megahertz band. The transmitted carrier signal is phase modulated with a continuous shift and a constant rate of phase change. This modulation is driven by a twin symmetrical pair of pseudo-random maximum length sequences.[21]

The GEOLOC system has some unique performance capabilities due to its tremendous process gain. Process gain is given by the ratio of the spectrum width (700 hertz) to the final useful bandwidth (.01 hertz for most ship applications). This ratio of nearly 10^8 corresponds to a capability of unwanted signals rejection of 78 decibels (rejection of skywaves or large natural reflectors' interference). This characteristic makes the system totally insensitive to any ionospheric distortions or other multipath signals. Also, due to the high process gain, the system requires only very low radiated spectral densities. It's radiated power is automatically and permanently controlled in order to follow the natural atmospheric noise evolution. In other words, the spectral density level of the signals are under the level of natural noise in nearby areas.[21]

There are basically two different ways in which GEOLOC can be set up: free-running mode and synchronized mode.

Free-Running Mode

In the free-running mode the time marks of the individual transmitters are not synchronized. Each transmitter uses a free-running CESIUM oscillator which provides very stable time keeping. The stable time keeping allows for a dead-reckoning position fix with random walk of only one to two meters per hour. If the mobile receivers use an on-board CESIUM time keeper, the location will be determined under a circular pattern of location lines. If the mobile receiver uses a good crystal oscillator, it will measure the difference of the transmitter signals' time of arrival and will locate them into a hyperbolic pattern of position lines. In either case an external accurate position update is needed from TRANSIT, NAVSTAR GPS, or some other accurate navigation system.[21]

Synchronized Mode

In the synchronized mode, the relative time and frequency drifts of the different transmitters of a chain are observed, corrected, and controlled by a common reference receiver. Synchronization between transmitters may be permanently kept within a few nanoseconds, which may alleviate the need for other position updates. This mode provides a hyperbolic pattern of position lines using a fully autonomous system.[21]

Operating Characteristics[21]

The operating characteristics of GEOLOC on Earth are as follows:

- Range = 1000 kilometers.
- Precision = 2 meters + 1 x 10^{-5} of distance from each transmitter.
- No "sky wave" interference, no phase ambiguity.
- No frequency allocation.
- No mutual interference with other band users.
- No limit to number of transmitters in a chain.
- Unlimited number of users.
- Permanent tracking of four stations in the mobile receivers.

- Position fix update rate = 10 seconds; position evolution = every second.
- Relatively light-weight transmitter stations and antennae may be set up everywhere, quickly, and at rather low cost.

Advantages and Disadvantages

For adaption to the lunar surface this system has many advantages over the other radio-beacon systems. Some of these advantages are as follows:

- High precision.
- No need for ionosphere for signal waveguidance.
- Not strongly affected by geologic conditions.
- Low power needs.
- Comparitively easy to set up.
- Can be autonomous.
- Fairly good range characteristics.

The main disadvantage of this system is in the potential high cost associated with the set up and maintenance of the beacon stations.

DESIGN SOLUTION

SELECTION OF THE FINAL DESIGN

The design team applied the Method of Pairs procedure to evaluate the design features and then a decision matrix to select the best overall navigation system for development of the lunar surface.

METHOD OF PAIRS

The pertinent features considered for evaluation of the systems were:

1. weight
2. coverage
3. reliability
4. accuracy
5. ease of implementation
6. operational ease
7. time required for operation
8. independence
9. maintenance requirements
10. expandability.

Through a sequential process, every possible pair of features was compared. A decision was made on which of the two features the design team considered more important, and a mark was placed by that feature. The weighting factor for each feature was then calculated by dividing the number of marks for that feature by the total number of marks. The Method of Pairs evaluation is given in Table 1.

The weighting factor for each feature is a number between zero and one, based upon the relative importance of the feature in supporting the overall goal

Table 1: METHOD OF PAIRS EVALUATION

FEATURES CONSIDERED	TALLY MARKS	TOTAL	WEIGHTING FACTOR
Weight	*	1	.0222
Coverage	**	2	.0444
Reliability	**●●*●●●●	9	.2000
Accuracy	**	2	.0444
Ease of Implementation	*****	5	.1111
Operational Ease	******	6	.1334
Time Required for Operation	******●●	8	.1778
Independence	*	1	.0222
Maintenance Requirements	****●●●	7	.1556
Expandability	****	4	.0889
Total		45	1.0000

of the design. The weight, independence, coverage, and accuracy features received the lowest weighting factors and were therefore considered to be the least important.

Weight and independence of the system are directly related to cost. Although cost was a consideration, the design team felt that performance and reliability should not be sacrificed for a light-weight system simply to reduce transport costs. In addition, the design team decided that cost should not be spared to provide a stand-alone (independent) system if a combination of systems could better meet the design criteria.

On the other hand, because the system was developed for preliminary phases of lunar base operations, complete surface coverage will not be necessary initially. Therefore, unnecessary dollars should not be spent to implement a sophisticated system that would provide continuous coverage of the entire lunar surface. However, system expandability is important to support later phases of lunar base operations. Hence, coverage received a low weighting factor and expandability a higher one in the Method of Pairs evaluation.

Finally, in evaluating accuracy, the design team required that each system be "accurate enough", or accurate within sight distance, to receive further consideration for development. Based on this requirement, the design team feels that dollars should not be spent to achieve 10 meters of accuracy when 30 meters would be sufficient. Therefore, accuracy received a low weighting factor.

DECISION MATRIX

In the decision matrix, the weighting factors for each feature and random rating factors for each system were multiplied to make a decision from the navigation systems under consideration. This matrix is given in Figure 5.

The initial result of the matrix indicated that inertial navigation was the best overall system. The design team eliminated this system from further consideration because the preliminary assumption of "accurate enough" was incorrect. The inertial mechanism contains highly sensitive gyroscopes that are easily knocked off heading. This problem is exaggerated when an astronaut is in a Moon rover, traversing the rugged lunar surface. In addition, an inertial system would require a separate system for calibration purposes. Current techniques use the Earth's magnetic field or gravitational pull which are nonexistent or insufficient on the Moon.

Of the remaining systems, the one with the highest decision factor was the ground-based radio-beacon system that operates on spread-spectrum transmissions. Celestial and satellite navigation systems each have drawbacks that were sufficient to place these systems at a lower ranking. The primary disadvantages of a celestial system are difficulty of operation, time required for operation, and accuracy. An astronaut in full space gear would have a hard time manipulating a sextant, tables of data, or a hand-held calculator. The time required for operation would be lengthy due to the amount of human effort involved in the operational processes (i.e., getting accurate star sightings and translating the star altitudes into latitudes and longitudes, either graphically or analytically).

Features Considered	*Weight*	*Coverage*	*Reliability*	*Accuracy*	*Ease of Implementation*	*Operational Ease*	*Time Required for Operation*	*Independence*	*Maintenance Requirements*	*Expandability*	**Totals**
Weighting Factors	.0222	.0444	.2000	.0444	.1111	.1334	.1778	.0222	.1556	.0889	1.0000
Celestial	10 .2220	10 .4440	9 1.800	3 .1332	7 .7777	3 .4002	3 .5334	10 .2220	6 .9336	8 .7112	**6.1773**
Navsat	1 .0222	10 .4440	7 1.400	10 .4440	1 .1111	5 .6670	8 1.4224	10 .2220	1 .1556	4 .3556	**5.2439**
Geostar	3 .0666	10 .4440	8 1.600	10 .4440	2 .2222	8 1.0672	8 1.4224	10 .2220	2 .3112	6 .5334	**6.3330**
Pulse-Matching Radio Beacon	4 .0888	10 .4440	6 1.200	8 .3552	1 .1111	8 1.0672	8 1.4224	10 .2220	1 .1556	4 .3556	**5.4219**
Spread-Spectrum Radio Beacon	5 .1110	10 .4440	7 1.400	10 .4440	4 .4444	8 1.0672	10 1.7780	8 .1776	4 .6224	7 .6223	**7.1109**
Inertial	10 .2220	10 .4440	9 1.800	1 .0444	8 .8888	7 .9338	8 1.4224	1 .0222	6 .9336	10 .8890	**7.6002**

Figure 5: DECISION MATRIX

FOLDOUT FRAME

Preliminary work has been done in adapting celestial navigation to the lunar surface. The associated errors are large due to gravity anomalies arising from the Moon's low gravity field and the presence of mass concentrations. These errors have been quoted as reaching 321.9 kilometers for rough calculations with no corrective terms applied. However, celestial navigation is the only truly stand-alone system to be used as a back-up method for astronauts in a "lifeboat" situation.

The main drawbacks of a satellite system are weight/cost, difficulty in implementation, and maintenance requirements. Currently, both operational and proposed satellite systems utilize some kind of ground-based master-control facility. The number, size, and complexity of the master stations vary from system to system. The cost associated with transport, set-up, and maintenance of these stations on the lunar surface would be significant, if not prohibitive. In addition, the orbital mechanics involved in establishing a satellite orbit around the Moon are complicated by the small mass and diameter of the Moon, as well as the gravitational pull of the Earth. Finally, since total coverage of the Moon's surface is not required for preliminary phases of lunar base operation, the cost associated with a satellite navigation system cannot readily be justified.

DESIGN DEVELOPMENT

Ultimately, the decision matrix evaluation led the design team to choose a variation of an existing ground-based radio-beacon navigation system called SYLEDIS. The design team developed the system for use in preliminary phases of lunar base operation with the assurance that it can be expanded for use in later phases.

In developing the SYLEDIS system for implementation , the design team has set certain guidelines concerning the mobility of astronauts on the lunar surface. These are as follows:

1. Astronauts are required to travel in pairs when outside the lunar base facility.
2. When on foot, astronauts must be within sight distance of the lunar base.
3. Astronauts must use a lunar rover when out of sight of the base facility.

SPREAD SPECTRUM VS. PHASE AND PULSE SYSTEMS

Radio-positioning is generally based upon the measurement of distances (range mode) or differences of distances (hyperbolic mode) between a mobile unit located at an unknown location (the user) and beacons located at known fixed positions. Measurements are usually based on either a phase comparison or a pulse-matching technique.

Phase Systems

Phase-comparison systems can make accurate measurements with relatively simple instrumentation and limited bandwidth requirements. Using higher frequencies improves the system resolution (accuracy), but two factors set an upper limit to this frequency:

1. Accurate positioning requires that wave propagation follow the surface of the Earth, and the range varies with the inverse of the frequency.
2. The ambiguity of phase comparison systems deteriorates as the frequency increases.

When the fundamental requirement of the system is accuracy, a compromise is found in the 2 megahertz frequency band. In this case, range is limited by skywave interference, and the lane width (100 meters or less) is too narrow for general navigation purposes.[24]

When range and ambiguity are the fundamental requirements, as is the case for navigation systems, frequencies in the 300 kilohertz or 10 kilohertz band are used.[24]

Pulse Systems

Pulse systems operate in the highest frequency ranges because good resolution (accuracy) requires sharp pulses only found in a broad spectrum, and bandwidth occupancy is limited by international or government regulations. At such high frequencies, range beyond the line-of-sight requires the transmission of a considerable amount of energy. High energies mean very high peak power is needed to produce sharp pulses, and high power requires costly and cumbersome equipment.[24]

Spread-Spectrum Systems

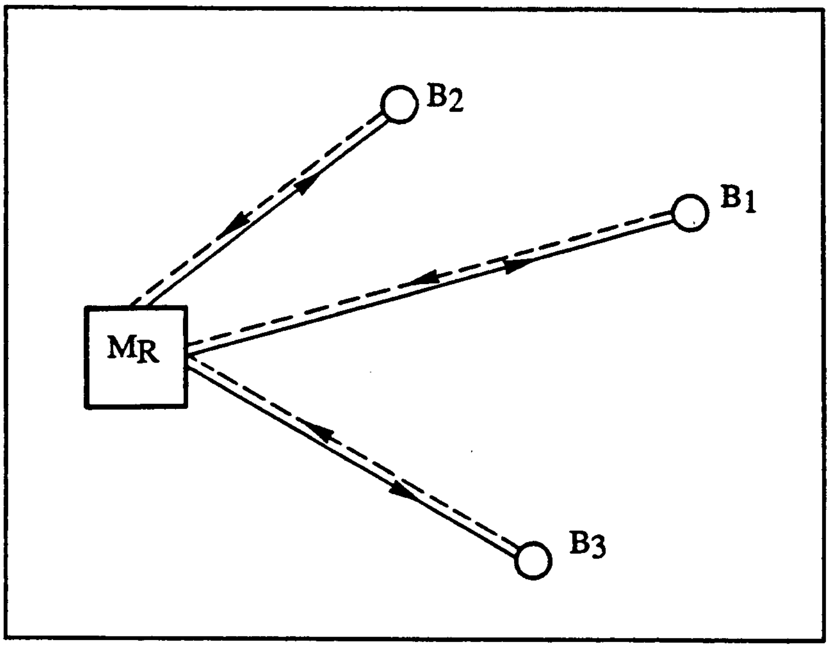
The SYLEDIS navigational algorithm is based on spread-spectrum transmissions. This type of operation is made possible by modulating the carrier signals with pseudorandom noise (PRN) codes. These carrier signals basically look like a noise band centered around a particular frequency. When the transmitted carrier is received, it is correlated with (multiplied by) a pseudorandom sequence that causes a sharp pulse. The arrival of pulses along the signal path is then timed to derive position information.

Spread-spectrum systems avoid the disadvantages of both phase and pulse systems. These systems use a correlation technique to obtain pulse compression, which increases the amount of energy available for each measurement and extends the range well beyond the line-of-sight using moderate peak power. The accuracy available from spread-spectrum systems is comparable to or better than that of the best 2-megahertz phase systems or of the pulse systems.[24]

PHYSICAL OPERATION

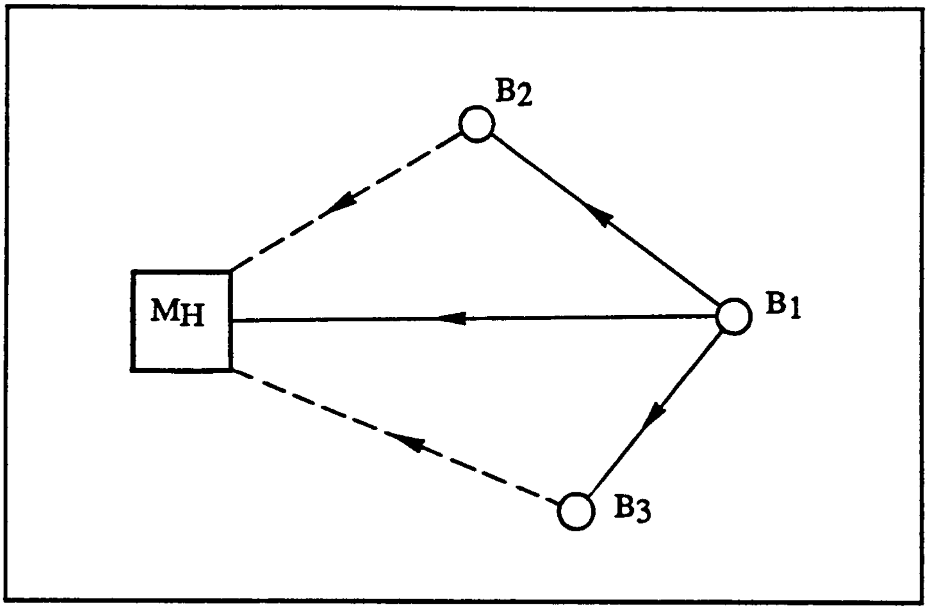
Figure 6 shows an example of a SYLEDIS cycle with three beacons (B_1, B_2, and B_3) and one mobile unit operating in a range-range mode (M_r). In the range-range mode, the mobile unit transmits a coded reference signal at time 00 simultaneously to beacons B_1, B_2, and B_3. Each beacon (B_n) receives the reference signal at a time $00 + \Delta_n$, where Δ_n represents the time-delay of the signal that is proportional to the distance between M_r and B_n. At times 01 to 03, beacons one, two and three, each in turn, transmit a coded signal back to M_r. By comparison with the reference signal, M_r measures the round-trip transit times of the signals ($2\Delta_n$), then calculates the distances to B_1, B_2, and B_3.[24]

Figure 7 shows a SYLEDIS cycle with three beacons (B_1, B_2, and B_3) and one mobile operating in a hyperbolic mode. In the hyperbolic mode, the coded reference signal is transmitted by one beacon B_1 at time 00 and received by the mobile unit M_h and two other beacons B_2 and B_3. At times 01 to 02, B_2 and B_3, each in turn, transmit a coded signal back to M_h. By measuring the time difference between arrival of the reference signal from B_1 and the coded



TIME SLOT	00	01	02	03
B1	R	C		
B2	R		C	
B3	R			C
MR	C	R	R	R

Figure 6: SYLEDIS CYCLE OPERATING IN THE RANGE-RANGE MODE



TIME SLOT	00	01	02
B1	C		
B2	R	C	
B3	R		C
MH	R	R	R

Figure 7: SYLEDIS CYCLE OPERATING IN THE HYPERBOLIC MODE

signals from B_2 and B_3, M_h calculates the differences of distances between itself and any two corresponding beacons.[24]

SPECIFICATIONS

The SYLEDIS system consists of mobile units, beacons, and antennae. The physical sizes and weights of the mobiles and beacons are given in Table 2.[25, 26]

Table 2: PHYSICAL DIMENSIONS OF MOBILES AND BEACONS

	WEIGHT	**SIZE**		
		Width	*Depth*	*Height*
MOBILE UNIT	16 Kg	435 mm	455 mm	177 mm
BEACON	16 Kg	448 mm	384 mm	177 mm

Power Requirements

The SYLEDIS system has a unique feature in its ability to "sleep" when not in use. During this period, called the stand-by mode, a designated master beacon "wakes" every 30 seconds and sends out a synchronized pulse. If there is no response from a mobile unit, the system continues in the stand-by mode. In this mode, the power consumption of the beacon is decreased from 50 watts to 7.5 watts.[24]

The power requirements for the mobiles and beacons are given in Table 3.[25, 26] To power the mobile units, astronauts will carry 24-volt Nicad (Nickel-Cadmium) batteries in their land rovers. Nicad batteries have distinct

Table 3: POWER REQUIREMENTS FOR MOBILES AND BEACONS

	MOBIL UNIT	BEACON
Power: DC Supply Voltage (Volts)	22 to 30	11-14 or 22-30 (automatic internal adaption)
Consumption (Watts)	55	10 to 50 (depending on operating mode) 7.5 in standby
Temperature: Storage	233 K to 343 K	233 K to 343 K
Operating	273 K to 328 K	253 K to 328 K

advantages over the lead-acid batteries more commonly used in solar applications. These are:

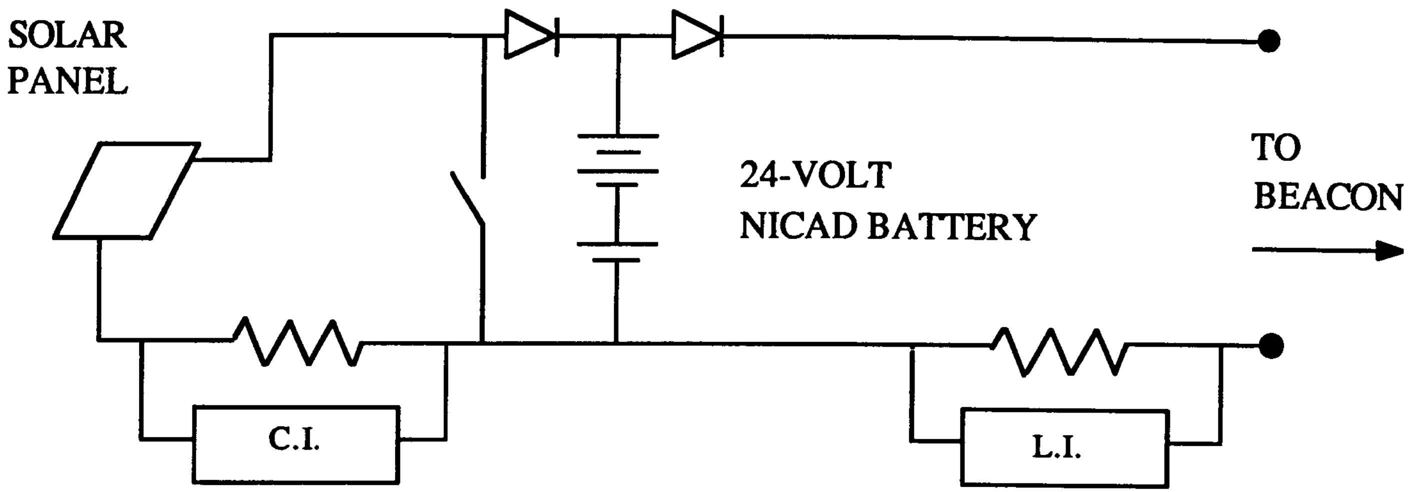
1. Ability to be overcharged without damage;
2. Ability to go for long periods only slightly charged without damage;
3. Mechanically more rugged, making them more transportable;
4. Ability to withstand freezing without damage.[11]

To supply power to the beacons, the design team proposes the use of photovoltaic solar panels in parallel with 24-volt Nicad batteries. A typical circuit is shown in Figure 8. The blocking diode B1 between the battery and solar array prevents the battery from losing charge through the array during times of darkness. This is particularly important on the lunar surface where solar panels will experience a worst-case period of darkness of approximately 14 Earth days. The regulator R protects the battery from overcharging by monitoring the voltage across the battery. Any excess power generated is dissipated as heat energy through the regulator.[29]

The output of a single silicon voltaic cell is typically .5 volts and 1 amp. The beacons require a power input of 50 watts (see Table 3). The array (n x m) needed to provide this power consists of 50 cells in series (n) and 2 cells in parallel (m). This is given by the equation[32]:

$P_{out} = n \times m \times P^{(1)}$
$P^{(1)}$ = power output of a single cell = .5 watts

This array size is based on the assumed power output of a silicon photovoltaic cell being .5 watts. Due to the lack of an atmosphere on the Moon and its orientation with respect to the Sun, the sunlight intensity on the lunar surface is



B1 = BLOCKING DIODE

C.I. = CHARGE INTEGRATER

L.I. = LOAD INTEGRATOR

R = VOLTAGE REGULATOR

Figure 8: TYPICAL PHOTOVOLTAIC SOLAR PANEL CIRCUIT

higher than that on the Earth. The power output of a solar array on the Moon can be increased up to five times that of a similarly sized array on the Earth.

The nominal required area for each panel may be estimated by:

$A = P_{out}/Q_s\eta$
$P_{out} = 50$ watts
Q_s = solar flux incident on a surface normal to the Sun's rays
= 1353 watts/meter^2
η = typical photovoltaic solar cell efficiency
= .15
A = .246 meter^2

This area must be adjusted to account for the incidence angle of solar irradiation on the panel's surface. The amount of solar irradiation decreases as the incidence angle increases. Hence, the required area increases in proportion to the incidence angle.

Operating Frequency

The basic SYLEDIS waveform is a modulated carrier selected in the 420 to 450 megahertz range. This frequency band is reserved for government use and therefore will not interfere with common radio signals. The modulating code is a 127-element pseudorandom sequence 66.66 microseconds long with .52 microseconds per element (see Figure 9). The correlation of the sequence is -1 everywhere except at zero where it is +127.

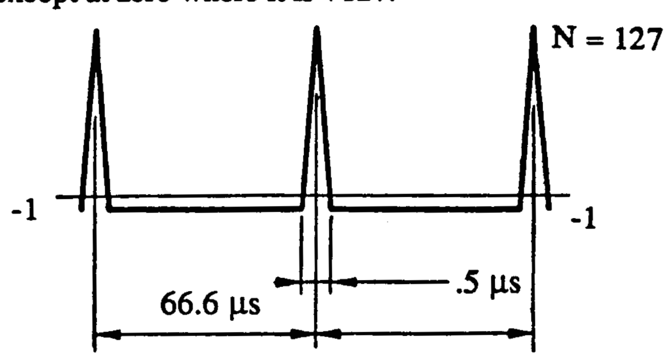


Figure 9: BASIC SYLEDIS WAVEFORM

Range

The range of the SYLEDIS system in kilometers can be estimated at between two or three times the line-of-sight between antennae on the Earth's surface. The line-of-sight (l.o.s.) between two antennae on the Earth is governed by the equation:

$$\text{l.o.s.} = 3.57\,(h_1^{1/2} + h_2^{1/2}),$$

where 3.57 = a conversion factor based on the curvature of the Earth's surface,
h1 = the height of antenna 1 in meters,
h2 = the height of antenna 2 in meters.

The range for the two beacons may then be determined by conservatively estimating a multiplication factor of 2.5 and multiplying by the line-of-sight.[24]

Due to the lack of atmospheric interference on the Moon, the multiplication factor will be significantly increased. On the other hand, the conversion factor will be reduced proportionally by the ratio of the Moon's circumference to the Earth's circumference. The lunar conversion factor (L.F.) is then:

$$\text{L.F.} = 3.57\,(D_M/D_E)$$
D_M = Moon's diameter = 3475 kilometers
D_E = Earth's diameter = 12756 kilometers
$\text{L.F.} = .973$

Since range is proportional to line-of-sight, the range available from two beacons on the lunar surface assuming a multiplication factor of 4.0 is:

$$\text{Range} = 4.0\,(\text{l.o.s.})$$
$$\text{l.o.s.} = .973\,(h_1^{1/2} + h_2^{1/2})$$

Increasing this range means increasing either the height or number of the antennae. Mission planners will decide on the size and number of antennae needed to provide the desired range. If they desire to travel to a remote location out of range of the primary system, astronauts have the option of carrying beacons and antennae with them in land rovers. These beacons/antennae may be dropped at strategic locations along the astronauts' path so that they can continually monitor their position relative to the base facility.

CONSIDERATIONS FOR LUNAR USE

Although the equipment and order of operation of the beacon system will remain essentially the same on the Moon as on Earth, certain adaptions are required for use in the hostile lunar environment .

RADIATION

On the Moon, the lack of a protective atmosphere allows for the same harsh radiation environment as is present in space. This radiation is comprised of both galactic cosmic rays (GCR) and solar energetic particles (SEP) from solar flares. The cosmic radiation bombarding the Moon consists mainly of relativistic and near-relativistic atomic nuclei ranging in energy from 10^8 to 10^{20} electron-volts. Approximately 98.6% of these nuclei consist of hydrogen and helium.[1]

Sensitive electronic instruments can be affected by both cosmic and solar radiation. Radiation damage produces changes in conductivity or shifts in device thresholds that cause a malfunction of the electronic circuit. Radiation-hardened components have been developed that can tolerate very large total doses as great as one mega-rad. These components make it possible to design lunar electronic systems with operational lifetimes in excess of ten years.[1] Using radiation-hardened components does not necessarily guarantee success in producing a radiation-hardened system, however. Some form of radiation shielding is also needed. Two basic techniques can be used for this purpose -- mass shielding by lunar regolith and reflective shielding.[22]

Mass shielding is an effective means of protection due to the abundance of lunar regolith and its density below the first few centimeters. System components can be buried beneath the surface layer to shield out most of the cosmic radiation. However, the hazard from secondary neutrons generated within the regolith by cosmic rays is a consideration.[13] By using both radiation-hardened components and mass shielding, the cosmic radiation effects on system electronics can be minimized.

Reflective shielding using special paints, polished metal oxides or metal foils that have a high reflectivity is a second means of shielding the components from incident radiation. These materials effectively block the harmful radiation rays by reflecting them, either angularly or diffusely, back into space.[4]

HEAT TRANSFER

Due to the lack of an atmosphere on the Moon, heat transfer is limited to radiation and conduction. This fact leads to some interesting heat transfer problems in the design of electronic systems for use on the Moon. Most areas of the Moon experience alternating periods of sunlight and darkness lasting approximately 14 Earth-days. During these lunar "days" and "nights", the Moon's surface temperature varies from 116 Kelvin to 366 Kelvin. Due to this temperature variation, instruments stationed on the lunar surface require protection against thermal fatigue, that is overheating or freezing of critical components. This problem can also be approached by two means -- mass shielding (insulation) or reflective shielding.

Mass Shielding

Mass shielding by regolith is effective due to the low conductivity of the lunar soil. At a depth of approximately one meter the regolith temperature varies between 198 Kelvin and 298 Kelvin.[13] Burying the beacons at one meter will eliminate thermal fatigue by avoiding the large temperature variations that occur on the surface (see Figure 10). Regolith shielding is also advantageous in that extra mass need not be added to the system for transport to the Moon. Thermal protection is provided using naturally occurring material.

Although a relatively thermally stable region exists below the surface of the Moon, it is difficult to transfer internally generated heat out of the system due to the low thermal conductivity of the regolith. Therefore, some means of heat transfer from the source is needed. A common means of dissipating heat from electronics in space is through a device called an evaporative coldplate. A coldplate is a passive closed-loop cooling system which consists of parallel copper plates with a wick of porous copper sandwiched between. The entire structure is sealed around the edges, evacuated, and partially filled with water. Electronic components are mounted directly on the cold plate. The generated heat is transferred to the outer edges of the cold plate and is conducted or radiated off. This heat transfer occurs when the water within the porous copper absorbs the heat and evaporates. The high energy vapor moves to the edges of the plate that are at a lower energy and condenses. After the vapor is condensed at the

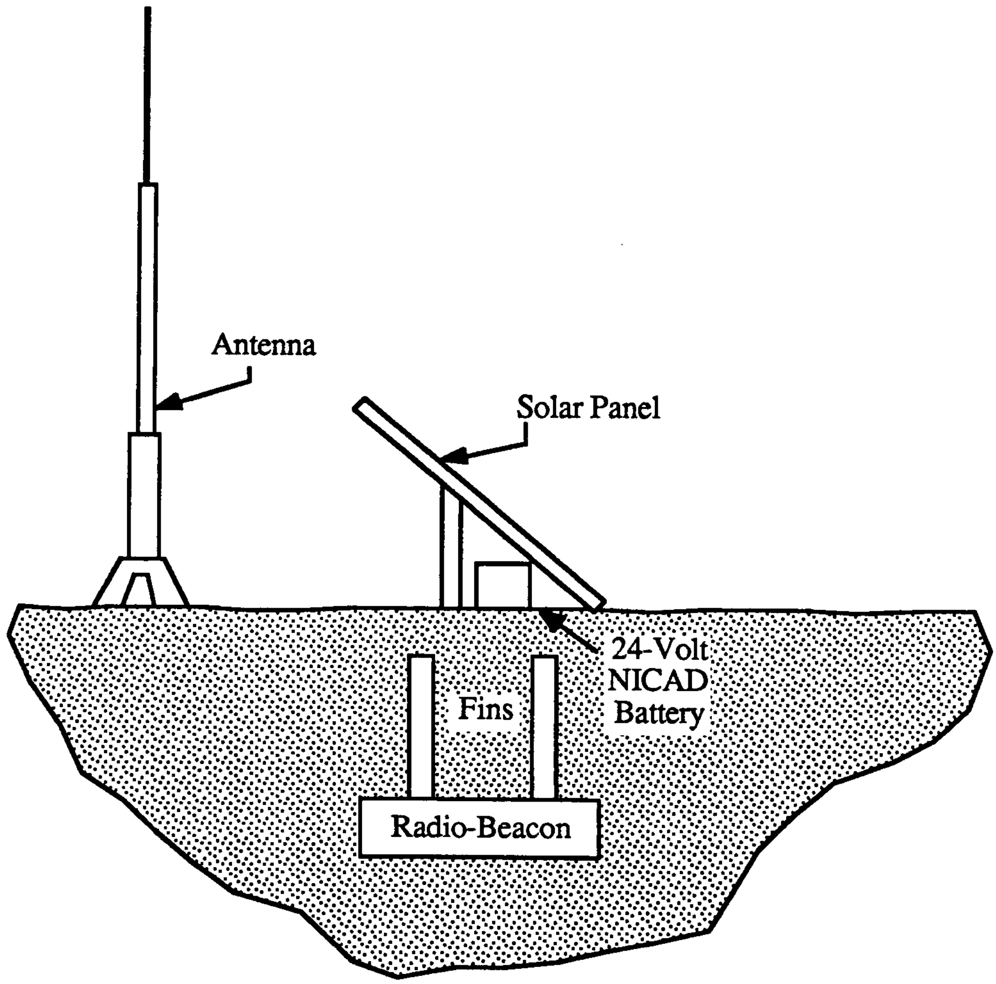


Figure 10: BEACON STATION WITH MASS SHIELDING

colder edges of the plate, capillary action through the wick forces the liquid back to the heat source.[6]

The main problem with cold plates in lunar application is ensuring that the edges remain at a lower temperature than the heat source. This may be difficult as the only natural means of heat transfer from the plates is either by radiation or by conduction through the regolith. The coldplates must therefore be extended to a large area for conduction to the soil or to a radiator for transmission back to space.

Reflective Shielding

Reflective shielding uses a coated protective structure with a high reflectivity to produce an area of shade for the equipment (see Figure 11). As there is no convection heat transfer on the Moon, reflecting the incident heat radiation will keep the equipment, as well as the ground beneath the structure relatively cool. Reflective shielding offers an advantage in that heat is radiated out of the system (i.e., the heat is not "locked in" by an insulator). To facilitate heat dissipation from the system, coldplates or radiators may also be required to extract any excess heat above the operating range. These coldplates will provide a conductive path to the regolith.

MICROMETEORITES

The lunar surface is continually bombarded by tiny galactic particles known as micrometeorites. These particles are on the order of one micrometer in diameter and travel at a velocity of 5 kilometers per second to 20 kilometers per second. Upon impact, the meteorite explodes and vaporizes, excavating up

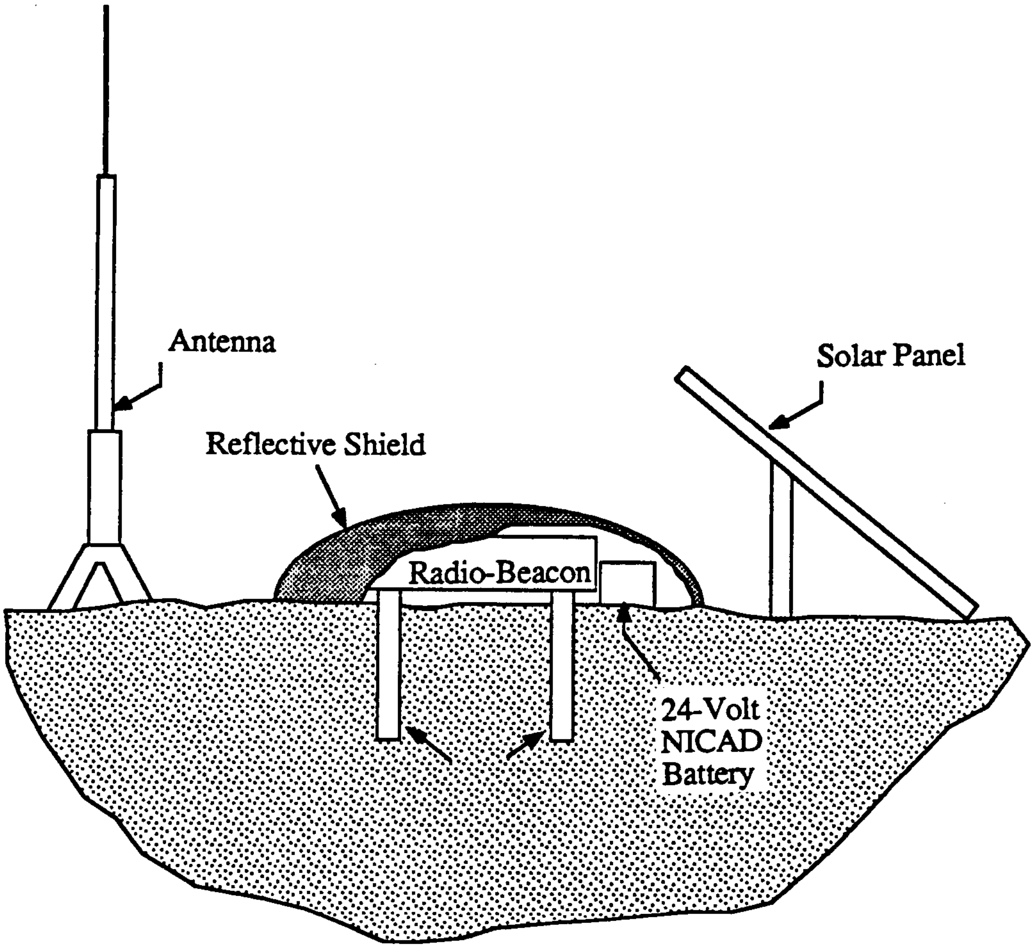


Figure 11: BEACON STATION WITH REFLECTIVE SHIELD

to 1,000 times its own mass. Due to this potential cratering, precautions must be taken to protect system components from extensive wear and erosion.[34]

For components buried in lunar regolith, micrometeorites pose no problem as sufficient shielding is provided. For exposed components, these micro-particles may cause degradation of the surface. Furthermore, erosion of small structural members constructed of relatively soft materials can occur. To protect surface finishes, impact-resistant glass coatings can be used. For structural members, impact-resistant materials can be used to minimize the effects of pitting.

VACUUM ENVIRONMENT

In addition to the above design considerations, the effect of the lunar vacuum on system components must also be addressed. Generally, electronic systems used on Earth cannot survive in a vacuum environment. Impurities and air bubbles in the components cause high pressure stress concentrations when placed in a vacuum. These stresses will cause malfunction and, in the case of air bubbles, will cause fracture of the part. Components can be built to low-impurity specifications that will survive in a vacuum environment. Hermetically sealing the system casings can offer further protection.

PROPOSED ADAPTIONS TO THE SYSTEM

To account for the above lunar environmental considerations, the design team proposes the following adaptions to the beacon navigation system.

MOBILE TRANSCEIVER

For use on the Moon, the transceivers will be built with radiation-hardened vacuum-adapted components. Since the mobile units will be mounted in the confines of lunar rovers and operated for relatively short time periods, the harsh lunar environment will not affect them significantly. Micrometeorite, cosmic radiation- and solar radiation-protection will be provided by the vehicle's shields and will keep the components within their operating ranges.

TRANSMISSION/RECEPTION ANTENNAE

For construction of the remote antennae Ti-6Al-4v titanium alloy will be used. This alloy is a light weight material which has high resistance to wear by micrometeorites.[34]

SOLAR PANELS

Careful consideration is necessary in adapting solar photovoltaic cells for use on the moon. Certain radiation frequencies must be absorbed by the solar panels in order to produce electron-hole pairs for generation of electric power. At the same time, irradiation in the far infrared region must be eliminated. Infrared radiation produces heat without contributing to the useful energy output. A spectrally selective cover slip must be added to provide large emissivity at long wavelengths, high absorptivity in the visible and infrared regions, and low absorptivity in the ultraviolet range.[11] In order to reduce the generation of excess heat, structural areas that radiate to the solar cells will be coated with a paint containing titanium oxide. Such paints have a ratio of absorptivity to emissivity of approximately 0.3 which will keep these surfaces relatively cool.[17]

Excess heat generated will be transferred by coldplates and radiators as discussed previously.

Other important considerations in implementing solar panels on the lunar surface include:

1. Lunar Dust. Lunar dust covering the panel reduces the amount of radiant energy absorbed by the panel and therefore the amount of current output. Monthly brushings are required at all remote sites to correct this situation.

2. Micrometeorites. Bombardment by micrometeorites will degrade the desired properties of the radiation shields, filters and the photovoltaics. To avoid this degradation, the solar panels will be covered with a layer of impact-resistant glass.

3. Vacuous Environment. The photovoltaic panels will be hermetically sealed to accommodate the Moon's vacuous environment.

REMOTE BEACONS

To protect the beacons from the lunar environment, the design team proposes the use of reflection shields (see Figure 11). These shields will be made of polished aluminum or a graphite composite to protect the electronics from cosmic radiation effects. The shields will also be coated with reflective paints containing titanium oxide to protect from solar radiation that produces heat. A layer of impact-resistant glass will cover the surface to avoid degradation from micrometeorites.

To further reduce the effects of radiation, the electronics will be made of radiation-hardened components that increase the operational lifetime up to 10 years. Electronics will also use vacuum-adapted components with no air bubbles or impurities.

The beacons will be mounted on copper legs (fins) extending into the lunar regolith to provide a conductive path from the coldplate to the regolith. Since the area under the shield will be constantly shaded, it will be at a lower energy (cooler) than the electronics, and heat transfer can occur by radiation.

The beacons use crystal oscillators that will not operate in extreme cold. The design team proposes the use of rubidium oscillators that generate more heat and can therefore operate in a colder environment.

CONCLUSIONS AND RECOMMENDATIONS

The design team feels the optimum navigating system is a radio-beacon method adapted for use in the lunar environment. A radio-beacon system provides a position fix well within sight distance and requires little input from the user. In particular, the SYLEDIS system includes a programmable tracking device, such that the user simply needs to program his course and the transceiver will visually display his progress. An astronaut in full space gear will easily be able to manipulate the system. Also, the SYLEDIS beacon station is light weight, minimizing cost, and will require little effort to implement. Small enough to assemble on Earth and transport to the Moon, the beacon station will be installed by inserting the copper legs into the regolith, connecting the beacon to the power supply, and turning on the unit. In addition, the SYLEDIS beacons can be calibrated and programmed from remote locations, making it particularly attractive for use on the Moon. Finally, radio-beacon navigation is the best solution for applications within a specified area. The SYLEDIS system will provide sufficient coverage for preliminary lunar base operations, and can readily accommodate the growth of these operations by installing additional beacon stations.

The lunar environment will greatly affect the operating characteristics of the system electronics. Radiation-hardened components have been suggested in order to provide protection from the incident cosmic radiation. Furthermore, specially developed electronics for use in a vacuum will have to be installed. Of particular interest is the transfer of heat to and from the beacon's electronic components in order to keep these components within a suitable operating temperature range. On the surface, the Moon's temperature will vary from 116 Kelvin to 366 Kelvin, and the only means of heat transfer is by radiation or conduction. In order to reduce thermal fatigue, the design team has proposed to protect the beacon from the incident thermal radiation by covering the device with a bowl-shaped structure coated with titanium-oxide paint (see Figure 11). This paint will not only limit the amount of thermal radiation to the beacon, but will also protect the beacon from the galactic cosmic radiation. The internal heat generated by the electronic components will be conducted to the coldplates, through copper legs and to the regolith. The size and number of required copper legs will increase with the amount of heat to be dissipated which increases with the power required. Also, the depth the copper legs are inserted into the regolith will depend upon the heat to be dissipated. The design team conservatively suggests inserting the legs one meters into the regolith, where the temperature is fairly constant at 223 Kelvin. Tests will have to be performed to determine the exact amount of heat to be dissipated, and then the actual depth to insert the copper legs can be calculated. Thus there will be a trade-off between the size, number, and position of the legs and the operating temperature of the system. The design team suggests further investigation concerning the heat transfer from the system electronics, an operating temperature range, and the size/number of copper legs to dissipate the heat generated. This investigation should optimize both the heat transfer from the system electronics and the associated cost.

The SYLEDIS system has proven to be very reliable in its Earth-based operations. An estimated mean-time-to-failure (MTF) of 10,000 operating hours has shown to be conservative. Also, the system is programmed to stand-by, or sleep when not in use. This protects the system electronics from burning up and is particularly attractive for remote locations where the beacons receive little use. Even so, there is the possibility the astronaut will find himself in a situation where he is unable to communicate with a beacon and cannot get a position fix. For such emergency situations, the design team suggests development of a backup for the primary system. Because celestial navigation techniques are independent of electronic devices, the design team further suggests celestial navigation for development into a secondary system.

Celestial navigation is the process of using the stars and other celestial bodies to define circles of position from which a position fix may be derived. As celestial observations are essentially the same for all spherical bodies, the practical application of celestial techniques is concerned primarily with the differences in terrestrial and selenographic aspects.[14] In addition, a primary consideration for development of celestial navigation for the Moon is the physically limiting space gear of the astronauts. The system should provide a position fix with minimal interaction between the astronaut and the equipment. The design team has identified three areas that require further development in order to implement celestial navigation:

1. Derivation of the tabular data used in celestial navigation. This includes charting the altitudes of the stars, measured

from the celestial horizon relative to the Moon at a known time and date. Several stars have been identified as candidates for this charting. The Sun is an attractive alternative because it is always within 1.5 degrees of the lunar celestial equator, but for approximately 14-day period the Sun will not be in view of the lunar observer. Zeta Draconis is a 3.6 magnitude star, 5.5 degrees from the lunar north celestial pole and may be used to indicate a north direction. Similarly, Delta Dorado is a fourth magnitude star, 2.0 degrees from the lunar south celestial pose. Polaris, more commonly known as the North Star, is within 22 degrees of the lunar north pole and Betelgeuse, with a terrestrial declination of N 7°23' is close to the lunar celestial equator.[14]

2. Development of an instrument to accurately measure the altitudes of the stars. This instrument will have to create an artificial horizon due to the lack of an elevation datum such as sea level on the Moon. A bubble octant used on Earth will result in an error of approximately one mile due to gravity anomalies and mass concentrations. Also, any altitude measuring device will have to compensate for refractive error due to the bubble-shaped visor surrounding the astronauts head.

3. Provide and analytical solver to compute position fixes. Several programs have been written to solve for latitude and longitude given the altitudes of two known stars and the time and date of observation.[30] These programs would have to be adapted for lunar use by transferring the altitudes and radii of circles of position to coordinates relative to the Moon.

The SYLEDIS system has proven to be reliable in extreme climates on Earth, and so with the proposed adaptions, will be suitable for use in the harsh lunar environment. A celestial backup will allow for navigation in the unlikely event the primary system fails. In conclusion, the ground-based radio beacon system, in conjunction with a celestial backup, will provide for the navigating needs of astronauts in all phases of lunar base operations.

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APPENDIX A: GLOSSARY

GLOSSARY

Age of the Moon - Expresses the position of the Moon in relation to the Earth and the Sun and can be estimated from its apparent phase as seen from Earth; one of the variables use to tabulate data in the American Ephemeris.

Altitude - The angular distance of a star, planet, etc., above the horizon.

Apogee - The point in the orbit of a heavenly body (usually the Moon) most distant from the Earth (opposed to perigee).

Aries - A constellation between Pisces and Taurus pictured as a ram.

Ascending node - The point in the moon's orbit where it crosses the plane of the ecliptic from south to north.

Ascension - The angle between the celestial meridian of an observer and the hour circle of a celestial object measured westward from the meridian; also called hour angle.

Azimuth - The arc of the horizon from the celestial meridian to the foot of the great circle passing through the **zenith**, the **nadir**, and the point of the celestial sphere of interest.

Bit - A unit of computer information equivalent to the result of a choice between two alternatives.

Celstial - Of or relating to the sky or visible heaven's <the Sun, Moon, and stars are *celestial* bodies>.

Celestial coordinator - A manual computer used for solving spherical triangles consisting of two spherical grids, one in the plane of the equinoctal superimposed on another in the plane of the horizon.

Celestial equator - The great circle on the celestial sphere mid-way between the celestial poles.

Celestial horizon - The great circle defined by the extension of the plane of the horizon until it intersects the celestial sphere.

Celestial pole - One of the two poles on the celestial sphere around which the diurnal rotation of the stars appears to take place.

Celestial sphere - An imaginary sphere of infinite radius on which the celestial bodies apear to be projected and of which the apparent dome of the visible sky forms half.

Dead reckoning - The determination with out the aid of celestial observations of the position of a vehicle from the record of the courses travelled, the distance made, and the known or estimated drift.

Declination - Angular distance north or south from the celestial equator measured along a great circle passing through the celesial poles.

Diurnal - Recurring every day or having a daily cycle.

Diurnal geocentric parallax - The displacement of a body owing to its being observed from the surface instead of from the center of the Earth.

Doppler effect - A change in the frequency with which waves from a given source reach an observer when the source and the observer are in rapid motion with respect to each other so that the frequency increases or decreases according to the speed at which the distance is decreasing or increasing.

Ecliptic - The plane of the Earth's orbit extended to meet the celestial sphere; the great circle of the celestial sphere that is the apparent path of the Sun among the stars or of the Earth as seen from the Sun.

Ephemeris - A tabular statement of the assigned places of a celestial body (i.e., Earth, Moon, satellite, etc.) for regualar intervals.

Ephemerides - Plural for ephemeris

Equatorial plane - The plane that passes through the equator of a celestial body.

First point of Aries - See vernal equinox.

General relativity - An extension of the special theory of relativity to include gravitation and related acceleration phenomena.

Geosynchronous - Of, relating to, or being an artificial satellite that travels above the equator at the same speed as the Earth rotates so that the satellite seems to remain in the same place.

Great circle - A circle on a sphere the plane of which passes through the center of the sphere.

Horizon - The plane parallel to the plane tangent to the Earth's surface at an observer's position but passing through the Earth's center.

Hour angle - See ascention.

Hour circle - A circle on the celestial sphere that passes through both celestial poles.

Inertial - Relating to a property of matter by which it remains at rest or in uniform motion in the same staight line unless acted upon by some external force.

Libration - A real or apparent oscillatory motion, esp. of the Moon.

Libration coordinator - A set of templates and indices which estimates the error caused by assuming the Sun to be on the lunar celestial equator and the Earth to be on the lunar prime meridian.

Limb - The outer edge of the apparent disk of a celestial body.

Mean center - The point of the lunar surface where the lunar prime meridian and the lunar equator intersect.

Mean libration - That time when all four limbs of the Moon are equally exposed.

Meridian - A great circle of the celestial sphere passing through its poles and the zenith of a given place.

Nadir - The point of the celestial sphere vertically beneath any place or observer and diametrially opposite to the zenith.

Nautical mile - Any of various units of distance used for navigaton based on the length of a minute of arc of a great circle of the Earth and differing because the Earth is not a perfect sphere; a United States unit no longer in official use equal to 6080.20 feet (1853.248 meters).

Parallax - The apparent displacement of an obfect observed, especially a heavenly body, due to a change of difference in the position the observer.

Perigee - The point in the orbit of a heavenly body, usually the Moon, that is nearest the Earth (opposed to apogee).

Poles of the ecliptic - The two points on the celestial sphere around which the Earth appears to rotate.

Prime meridian - A meridian from which longitude east and west is reckoned.

Selenocentric - Of or relating to the center of the Moon; referred to or involving the Moon as the center.

Selenographic - Of or pertaining to the physical features or geography of the Moon.

Semi-diameter - The apparent radius of a generally spherical celestial body.

Special Relativity - A theory which is based on the two postulates (1) that the speed of light in a vacuum is constant and independent of the source of the observer and (2) that the mathematical forms of the laws of physics are invariant in all inertial systems and which leads to the assertion of the the equivalence of mass and energy and of change in mass, dimension and time with increased velocity.

Spherical error probability (SEP) - Given by the probability of the navigation error being less than fifty percent.

Vernal equinox - One of the two points on the celestial sphere where the celestial equator intersects the ecliptic; also called the first point of Aries.

Zenith - The point of the celestial sphere vertically above any place or observer, and dimetrially opposite to the nadir.

APPENDIX B: SERCEL SYSTEM COMPONENTS

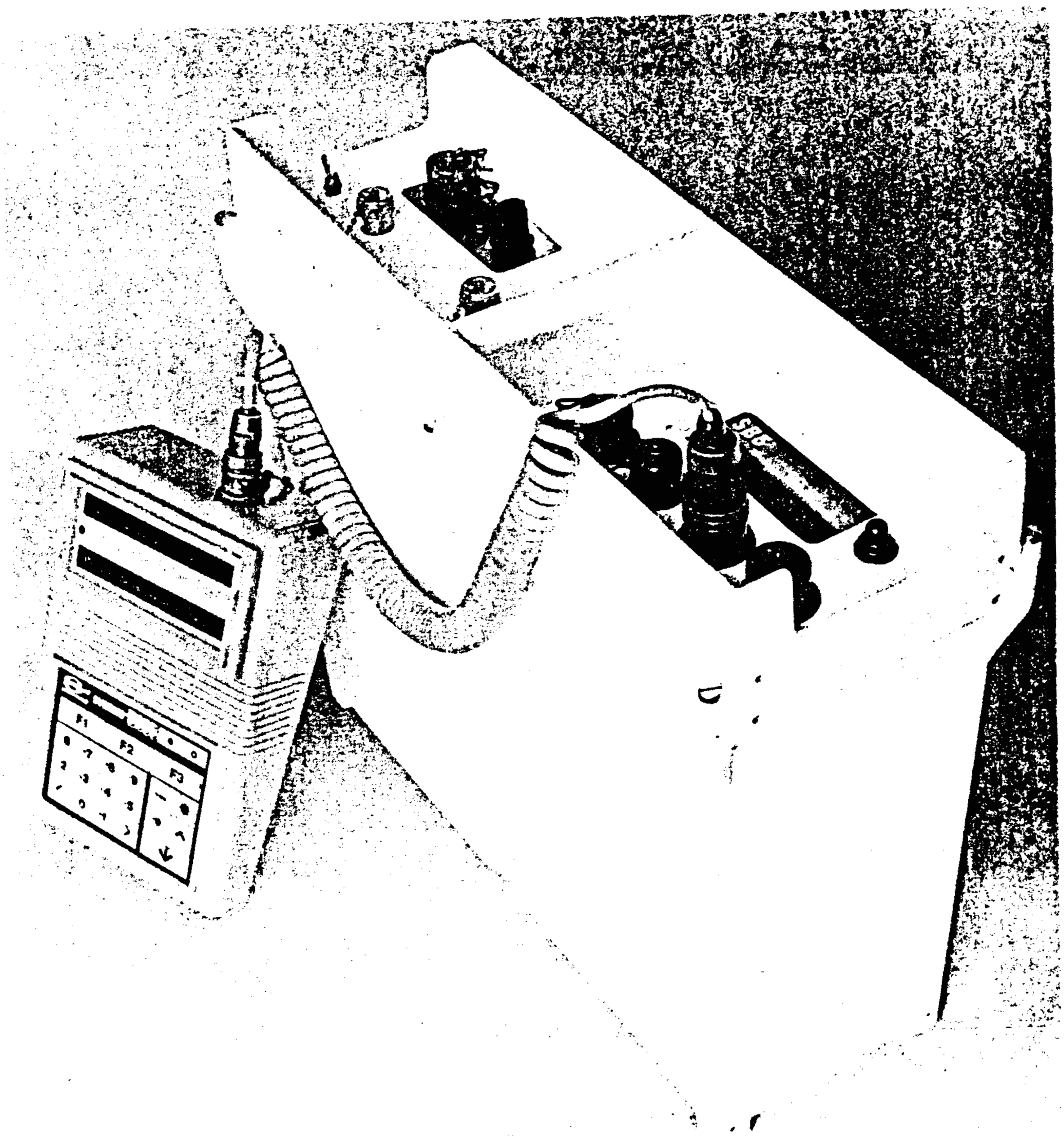

Figure 12: SYLEDIS BEACON UNIT

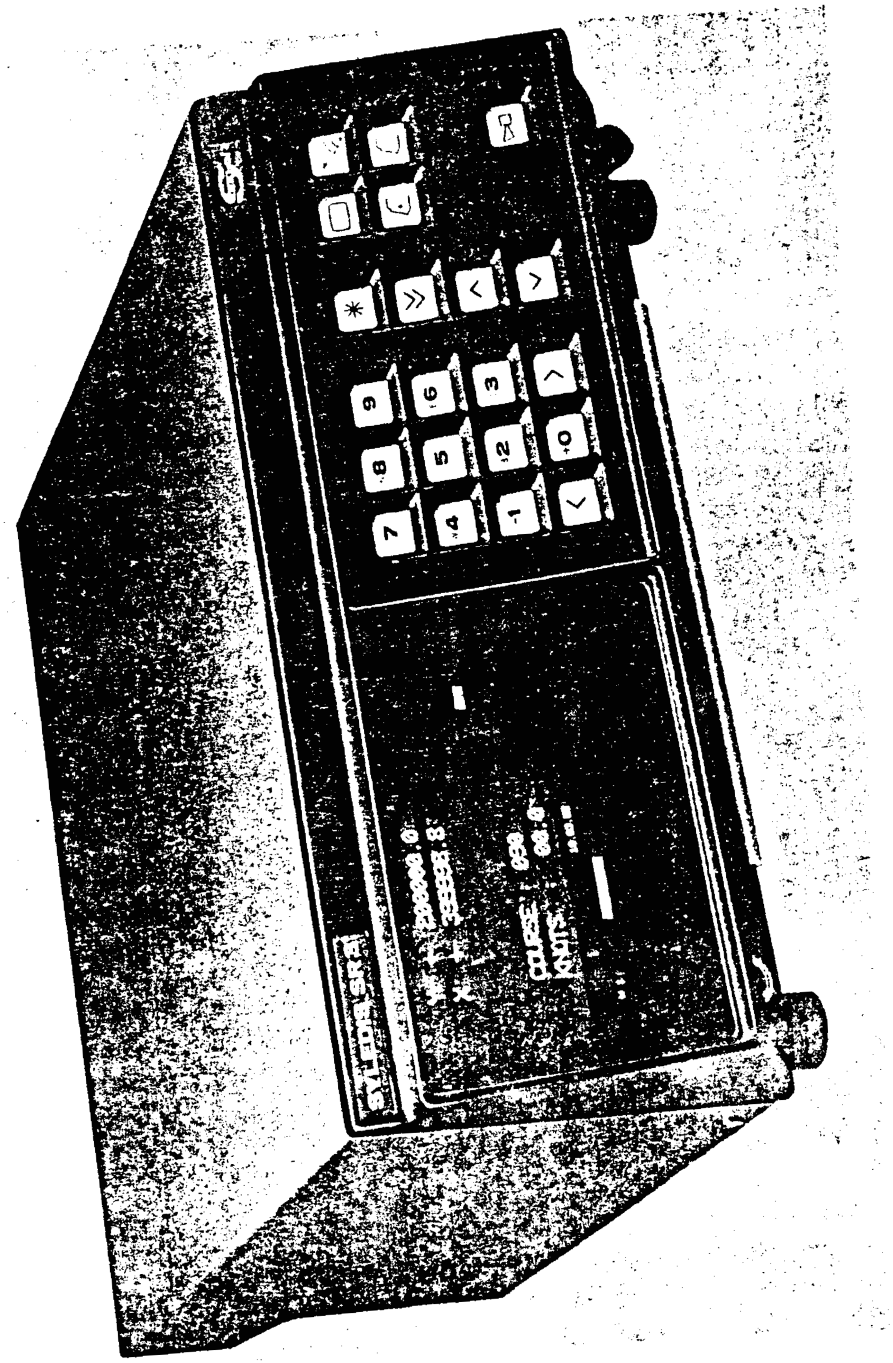

Figure 13: SYLEDIS MOBILE UNIT

APPENDIX C: RELATED ARTICLES