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Abstract

This study concerns itself with one aspect of possible post-Apollo space activity -- a program of astronomical research on the moon that culminates in the establishment of a lunar observatory. A mathematical model is utilized to analyze the logistics implications of conducting such an astronomical research program. The nature of the research equipment needed for the accomplishment of the program is outlined. Superposition of this research program upon a basic long-term lunar-base operations plan tentatively indicates that it could be feasible to conduct such a program of research during the 1970's and 1980's well within the constraints imposed by the logistics of presently planned spacecraft, boosters, and launching facilities. Although the best available numbers were used, the present study is viewed more as an exposition of a methodology than as the establishment of a conclusive result.

Introduction

In a recent memorandum,[1] a mathematical model was developed to evaluate various aspects of the logistics supply support of space bases. This model plans a sequence of trips, their dates, and the composition of the cargoes needed on each trip to satisfy a series of supply requirements over a time spectrum imposed by the activities at the space base. The scheduling model can be used in two different modes: (a) as part of a control system for an actual space base, or (b) as a planning tool to aid in the design of a space base and the formulation of operations schedules.

In the earlier study,[1] the model was illustrated in terms of a lunar base operation[2] over a two-year period. In the present study, we superimpose the requirement to deliver scientific equipment necessary to conduct astronomical research and build an observatory on the moon upon the "regular" requirements of a permanent lunar base over an eight-year period. Using the model,[1] we are able to obtain some idea of the marginal stress put on the supply system by the astronomical research program, and obtain an indication of the logistic feasibility of the postulated research program.

The actual numerical results should not be interpreted as though they pertained to a proposed program of research. They serve to show the capability of the developed methodology to evaluate quantitatively the implications of superimposing demanding scientific requirements on an existing or planned supply-support system for space operations. The study itself illustrates how detailed logistics considerations could be introduced in the early planning phases of future space missions.

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Astronomical Requirements

General Considerations

In order to use fully the inherent capabilities of the space-base supply-system model,[1] the scientific program to be evaluated must be developed in realistic terms. In the following discussion of astronomical research on the moon, even though we develop a detailed scenario, we wish to avoid two basic fallacies frequently present in research planning. The International Geophysical Year effort has taught us that it is difficult to plan a comprehensive research program solely on the basis of eminent advice and abstract ideas from the scientific community. Rather, one must find capable scientists willing to conduct specific research projects and build a program on and around such committed efforts. NASA's experience in planning its space program seems to reinforce this concept.

Planners also should avoid attempts to preplan in minute detail the "discoveries" to be made by a research program. What must be planned is the provision of basic equipment to enable the researcher to investigate the phenomena he finds intriguing. It is the researcher, not the planner, who is better able to design and use the terminal instrumentation that must be added to the basic equipment in order to permit a scientific experiment to be performed.

It should be kept in mind that observational astronomy is essentially the detection and analysis of electromagnetic radiation over the accessible range of frequencies. In general, a telescope is merely the basic equipment mentioned above. The individual experimenter adds his specific terminal instrument, be it a camera, photometer, or spectroscope, to the telescopic system at the specific focus that best meets his demands. Our discussion reduces itself, therefore, to (a) an examination of the basic equipment and facilities that could be erected advantageously on the moon in order to permit detection and amplification of electromagnetic radiation, and (b) guesses concerning the terminal instruments that experimenters -- on earth or on the moon -- may wish to have in operation on the moon at one time or another for one purpose or another.

The potential value of the moon as a site from which to perform astronomical research has received considerable attention in recent years.[3--7] Discussions frequently have been limited to rather general considerations of the advantages and disadvantages of a lunar observatory compared to existing earth-based and potential earth-orbiting observatories. These arguments will not be repeated here. We grant without argument that there are astronomical studies that, for physical or economic reasons, (a) cannot be done from the moon, (b) can be done better from earth or from an earth-orbiting satellite than from the moon, or (c) cannot be foreseen at this time. We maintain, however, that basic equipment provided for lunar astronomical research should allow for maximum freedom of choice in order for the actively interested experimenter to conduct, or have conducted, the astronomical studies he wishes to pursue.

Based on the above considerations, a scenario for a lunar astronomical research program has been developed to fulfill the input requirements of the space-base supply-system model. The scenario and the resulting program requirements are described in this section in terms of a possible sequence of events that are detailed sufficiently to serve this purpose. We believe that our sequential approach is the most realistic one possible at this time if one is to evaluate logistically the plans for a full-fledged lunar observatory a decade or two in the future.

Each sequential step contains a listing of support requirements that will satisfy the scientific objectives of the period. The astronomical requirements are divided into two categories: (a) basic equipment and facilities; (b) terminal scientific instrumentation.

The estimates of net weight do not include extensive packing material or complete provisions for protection against acceleration or vibration forces. They have sufficient validity to serve as input for a logistic model but should not be considered the actual weights of specific instruments.

The estimates of dimensions and volumes are schematically representative of rectangular boxes that would cover the required structural dimensions. Larger equipment is divided into the appropriate numbers of boxes needed to transport components for the complete structure. Depending on the amount of assembly visualized as taking place on the moon, larger boxes could -- in most but not all instances -- be further subdivided into smaller units.

It must be emphasized that the weight and volume data are strictly a first-order approximation. Elementary considerations will indicate that the nature and availability of such natural resources on the moon, as rocks, small craters, and the possibility of tunneling, can vary these basic data by large factors. Further, the ingenuity of local personnel and the possibility of laying out optical structures over wide terrain areas could significantly alter these numbers.

A sequential process of program planning can, however, be adapted to meet such changes in logistic requirements. It can also provide for such potential problems as the deterioration of optics due to meteoritic impact, the degradation of equipment from cosmic rays, and the erection of large structures in a vacuum.

Pre-Apollo Period

Before the first astronaut has landed on the moon, we can expect to witness the initial launchings of Orbiting Astronomical Observatories (OAO)[8] and additional launchings of the already successful Orbiting Solar Observatories.[9] Concurrently, Surveyor spacecraft[10] will be soft-landed on the moon to conduct *in situ* experiments from the surface of that body. It would appear that exploratory astronomical observations could be readily performed from one of the planned Surveyors. Barring the resurrection of the recently completed Ranger program,[11] such observations would mark the beginning of a lunar astronomical research program.

Relatively simple, automatic instrumentation similar to that being developed for the first few orbiting astronomical observatories should be adaptable to the lunar surface environment. Even a very small telescope exploring the ultraviolet region of the spectrum could obtain new and useful data. It could survey the sky, using data-collection and -transmission principles developed for the OAO project and could be employed as a simple transit instrument to obtain data on the libration of the moon. Such an instrument would be quite useful as a tool for examining the earth as a planet.

By merely being in operation, however, a small telescope might achieve its greatest usefulness as a site-survey instrument similar to those now employed on earth. Routine observations might, for example, determine through the twinkling of stars any remnant of lunar atmosphere, deterioration of optics from meteoritic impacts or other causes, and the general illumination characteristics of the location and of the "lunar sky."

Apollo Flights

Experience gained during the pre-Apollo period would be advantageous but is not mandatory to the conduct of astronomical experiments during early Apollo flights. Three activities can be distinguished:

(a) Astronomical observations by astronauts aboard Apollo spacecraft in test flights and in circumlunar orbits;

(b) Simple astronomical observations by astronauts during their periods of stay on the lunar surface;

(c) The activation, use, or servicing of semiautomatic astronomical equipment on the lunar surface by "visiting" astronauts.

A complete scenario of this period must further take into account the probable existence of unmanned solar and astronomical observatories and planetary spaceprobes. It must also allow for the state of progress of manned laboratories in orbit around the earth. An abundance of astronomical data should be available from these sources.

Table 1 -- Astronomical Requirements During the Period of Early Apollo Flights

Basic Equipment and Facilities	Net Weight (lb)	Volume
Semiautomatic Telescope, 6" (with finder telescope)	50	50" x 12" x 12"
QUESTAR Telescope	11	14" x 7" x 7"
Chronometers	50	15" x 15" x 8"
Occultation Devices	20	12" x 12" x 12"
Terminal Scientific Instrumentation	**Net Weight (lb)**	**Volume**
Filters (box)	5	12" x 6" x 6"
Camera	5	12" x 6" x 6"
Astronomical Plates (boxes)	25	5 x [6" x 6" x 2"]
Spectroscope (attachment)	10	
Recording Photometer	15	3 x [6" x 18" x 18"] (Spectroscope, Photometer and Data Storage Unit together)
Data Storage Unit	10	

Examples of astronomical observations in the field of eclipse research have been discussed in detail in earlier studies. It has been shown[12] that astronauts' observations of eclipses, transits, and occultations from orbiting spacecraft will provide data of value to astrophysics and geophysics. For observations made by astronauts from the surface of the moon, specific instrumentation and types of observations[13] have been suggested. These studies concentrate on relatively simple experiments, based on the assumption that early astronauts will have only limited experience and training as astronomical observers.

An important task for lunar astronauts may, therefore, be the use and activation of semiautomatic equipment that has been landed on the lunar surface before or concurrent with their arrival. A variety of important experiments could thus be conducted that fully automated instruments could not perform as easily or economically. The modest astronomical requirements imposed on a logistics supply system during this period are listed in Table 1.

As has been emphasized before,[13] we should not be under the illusion that early experiments need be complicated in order to make tremendous progress in many areas of astronomy. As of the time of this writing, for example, even such elementary problems as the rotation period of Mercury or the mass of the moon are unsolved.

Apollo Follow-on

During the 1970's, our scenario assumes that the use of the moon as an advantageous site for astronomical observations will begin to accelerate. Automatic equipment could perform sky surveys over a wide range of frequencies -- from the X-ray and ultraviolet region of the electromagnetic spectrum to the far infrared. A small reflector of 6" to 12" aperture could be employed as the basic equipment. Useful spectroscopic and photoelectric analyses of ultraviolet and infrared sources would be possible.

Even with such simple equipment, survey problems in positional astronomy, planetary astronomy, solar physics, and to a limited extent stellar and galactic astronomy, could be investigated. Specific investigations such as eclipse research could be conducted most fruitfully by the astronauts themselves. They would primarily handle raw-data acquisition with the equipment and instruments available.

In the pre-Apollo period, we limited ourselves to postulating rather moderate requirements for basic equipment and terminal instrumentation. During the Apollo follow-on and subsequent phases, however, it would appear logical to assume that lunar astronomical activity should gradually begin to resemble, on a rather reduced scale, similar activity at an earth-based observatory. Table 2 is a listing of astronomical requirements based on this assumption.

Table 2 -- Astronomical Requirements During the Period of Apollo Follow-on Activities

Basic Equipment and Facilities	Net Weight (lb)	Volume
Reflector Telescope (Cassegrain 10")	600	2 x [60" x 24" x 24"]
Meridian Transit Circle and 3" Refractor (without pier)	1000	3 x [60" x 24" x 24"]
X-ray Telescope	100	24" x 12" x 12"
Darkroom (old LEM?)	---	---
Terminal Scientific Instrumentation	**Net Weight (lb)**	**Volume**
Visual Micrometer	20	36" x 24" x 12"
Visual Photometer	20	36" x 24" x 12"
Thermocouples	100	48" x 36" x 36"
Monochromatic Filters	25	5 x [12" x 6" x 6"]
Spectrograph	400	60" x 36" x 36"
Darkroom Supplies (including chemicals, water, plate cutter, pans, etc.)	1000	Series of boxes

Table 3 -- Astronomical Requirements During the Period of Post-Apollo Activities

Basic Equipment and Facilities	Net Weight (lb)	Volume
Schmidt Camera	2000	2 x [6' x 3' x 3']
Coronagraph	800	5' x 2' x 5'
Radio Astronomy Antenna Net	(miles of wire)	(1 mm diameter)
Micro-Densitometer	1500	2 x [6' x 3' x 3']
Blink Comparator	500	3' x 3' x 3'
Measuring Engine	200	2' x 1' x 1'
Linear Comparator	500	3' x 3' x 3'
Machine Shop	1000	suitable
Terminal Scientific Instrumentation	**Net Weight (lb)**	**Volume**
Recording Photoelectric Photometer	400	3' x 3' x 3'
Telescope Accessories	600	2 x [3' x 3' x 3']
Image Converters	250	3' x 3' x 3'
Polarimeter	150	3' x 1' x 2'
Infrared Spectrometer	200	4' x 3' x 3'

Post-Apollo

With the advent of permanent, or at least indefinite, human occupancy of the moon, a new era of astronomy is postulated to begin. For our scenario, we shall assume that there is a gradual change from astronomical observations of a survey nature to the conduct of research projects. Initially, the researcher probably remains on the earth, while a "night assistant" on the moon gathers the data. Activities benefit from correlated research projects involving the simultaneous use of orbiting solar and astronomical unmanned observatories, planetary probes, and manned orbiting laboratories. It should be emphasized, however, that significant analysis, interpretation, and calibration of data depends most heavily on the conduct of correlated research at earth-based observatories.

Likely major equipment for the lunar astronomical facility includes a reflecting telescope and a Schmidt camera. Further, it is rational to include in our scenario, surface locomotion and exploration that permit the erection of ground antenna nets for use in radio astronomy. These nets are laid out where they will be shielded from earth-generated electromagnetic noise -- in a deep crater, perhaps, or in a location where the earth is on the moon's radio--optical horizon.

Certain activities, such as the tracking of earth satellites and space probes, constitute a challenge to maximum use of available instruments. Low-temperature circuits and solar power supplies play a determining role here. The rate of progress, however, depends also on the availability of natural lunar resources.

During this period, it can be expected that logistic and economic constraints, rather than scientific desirability alone, will determine when equipment of a specific size can be transported to the moon. Although Table 3 lists the estimated astronomical requirements for this period, no absolute time scale can realistically be given. As will be shown later, application of the space-base supply model can provide useful information for just such a problem situation.

Lunar Observatory

It can be assumed that the site of the principal lunar observatory will be on the side of the moon facing the earth. Except for radio telescopes, this location would not present a problem for astronomical research that could not be solved with suitable occultation equipment. Recall that the moon probably has no more than a very tenuous atmosphere and that the earth remains relatively fixed in the sky at all times for a given location on the moon.

As mentioned, the basic equipment provided, limited only by logistics, economics, and the ingenuity of the local personnel, will determine

Table 4 -- Typical Astronomical Requirements of a Lunar Observatory

Basic Equipment and Facilities	Net Weight (lb)	Volume
Reflector, 36" aperture	8000	2 x [18' x 6' x 6']
Astrograph, 10" aperture	6000	2 x [12' x 3' x 3']
Solar Telescope, 40" aperture	10000	4 x [18' x 6' x 6']
Infrared Telescope	6000	3 x [12' x 6' x 6']
Coude Spectrograph Attachments	2000	4 x [6' x 3' x 3']
Spectroheliograph	2000	4 x [6' x 3' x 3']
Parabolic Radio Disk, 28'	25000	25 x [6' x 3' x 3']
Large Reflector, 60" aperture	40000	1 x [5' x 5' x 3']
		+ 40 x [6' x 3' x 3']
Terminal Scientific Instrumentation	**Weight/Month (lb)**	**Volume/Month**
Variable, including Expendable Supplies	1000	6' x 3' x 3'

what research areas should be most actively pursued. Lightweight terminal instruments would, therefore, present no limit to the vast possibilities for astronomical research.

Experience with astronomical research on our planet to date, however, suggests that a limiting factor would be the number of astronomers interested in obtaining and analyzing data available from a lunar observatory. Finally, again from experience, the interests of the astronomer(s) in residence at the lunar observatory might determine what area of research would be stressed, be it galactic astronomy, celestial dynamics, or a search for planets of nearby stars.

Table 4 represents an estimate of the logistic requirements of a lunar astronomical observatory capable of conducting a wide range of research projects. To obtain some indication as to whether these scientific desires are compatible with logistic realities, and if so, when we could expect to actually realize an astronomical observatory on the moon, we shall now turn to the mathematical model of supply support for answers.

Space-Base Supply Model

Capabilities of the Model

The mathematical model, which is more fully described in Ref. 1, is a remarkably flexible tool for the planner. It can be programmed to simulate all principal steps in the logistic operation from supplier or manufacturer to the use of the supplies at the base. Once the requirements and restraints have been input, the computer can find and describe a feasible schedule (if any) for getting the supplies to the base in the right sequence within the required times, with the specified vehicles, subject to such limitations as weight and volume capacity of each vehicle, rate of supply, number of available launch pads, and maximum or minimum permissible interval between launches.

If desired, the requirements and restraints can be varied (for example, on the basis of what is learned in the first run) to reveal what effect on schedule these variations create. Likewise, the nature of the base's mission might be expanded or contracted on the basis of first results, and a new run made on the computer to show what constraints must be relaxed (or could be tightened), or what additional or reduced logistic effort is required as a result.

Input Data

Before using the mathematical model to analyze the logistic requirements of the lunar astronomy program described earlier, two steps had to be completed to prepare the necessary input data. First, the illustrative example of the study reported in Ref. 1 (namely, the requirements for a two-year period of operation of a manned lunar base) was extrapolated to an eight-year period, although the plan of operation calling for permanent occupancy by six men was retained. Secondly, the astronomical program requirements were translated into logistic data suitable for the model.

All input data for the model are summarized in tabular form in the Appendix. The tabular entries are listings of base-supply modules and logistics carriers. Weights and volumes are rounded to the nearest pound or cubic foot.

The basic unit element is the supply module -- to be thought of as a detachable or removable subassembly with a specific function or functions. It is identified by a number and a descriptive term indicative of its content. Each astronomical module is identified by a three-digit number followed by the letter A.

Each trip has been assigned a logistics carrier -- to be thought of as a spacecraft that contains modules as payload. A logistics carrier may itself serve a major module function such as providing shelter. To distinguish a carrier from a module, the identification number and volume of the former are listed in parantheses. Note that a carrier for a given trip provides volume capacity to be filled by supply modules.

Month zero is designated as the time of the first landing of base personnel. Each tabular entry contains both the month of earliest possible delivery and the month of latest possible delivery with reference to month zero.

The first table in the Appendix (Table 8) consists, for the most part, of the base supplies planned for the original two-year period plus eight carriers required to deliver them. The modules and carriers in Table 9 are those needed for the additional six years of base operations. Table 10 is a list of astronomical modules, which contain astronomical equipment and supplies that must be delivered in order to conduct the astronomical program outlined earlier.

Input Considerations

The delivery of the regular supply modules listed in Tables 8 and 9 would support the lunar base for 96 months, given no unforeseen or emergency events. The latest possible time of delivery for each module is derived from an analysis of operations at the base, which indicates when certain modules will begin to be used according to the base's need for the supplies contained in that module. Earliest possible time of delivery is a function of radiation and meteorite dangers and potential changes in the operations plans due to contingencies or discoveries or both.

Necessary shielding weights are based on the earlier study,[1] leading to a maximum desirable period of 24 months between earliest and latest possible delivery times for modules subject to radiation and meteoritic damage. A negative earliest possible delivery time implies that the module could be delivered prior to month zero, the time of the first landing of base personnel.

It would be preferable to deliver the astronomical equipment and supplies in the same general order as discussed earlier. Arbitrary earliest and latest possible delivery times were attached to the astronomy modules (Table 10). However, the time intervals chosen were broad enough to ensure that the research could be undertaken without imperiling the build-up of regular operations and the safety of the base, the personnel, or the entire logistic supply system.

Results From the Model

Computer Output

With the input data detailed in the Appendix, two basically satisfactory computer runs will be discussed here. In the first, delivery of the regular supply modules and necessary carriers listed in Tables 8 and 9 was called for, and a satisfactory schedule was produced. The resulting trip-delivery schedule to the lunar base, permitting its operation for a period of eight years, is summarized in Table 5.

In the second computer run, delivery of the same modules and carriers was called for, but now the astronomical modules of Table 10 were added. The results are summarized in terms of a logistic delivery schedule, in Table 6. They represent the orderly logistic effort required to support the base plus an extensive lunar astronomical research program for eight years.

Analysis of the results of both runs indicated that a three-pad Saturn V launch complex with pad-turnaround times of one month can handle the required traffic. Payload weights on the 16 trips of the first run ranged from 22,720 to 26,080 pounds. The second run required 23 trips with payload weights ranging from 22,780 to 25,100 pounds. Assuming an average payload capacity of 25,000 pounds per launch for the Saturn V, slack on trips can be viewed as contingency allowance.

In the course of the study the volume of the astronomical equipment was found not to be a binding restraint on the launch system. About

Table 5 -- Results of First Computer Run (No Astronomical Modules)*

Trip	Total Weight (lb)	Earliest Delivery (month)	Latest Delivery (month)	Modules and Carriers
1	23,337	-9	0	1; (6); 21; 25; 37
2	23,209	-2	0	(13); 19; 20; 22; 27
3	22,720	0	3	(43); 55-58; 60-62; 125
4	22,820	7	7	2; (9); 14; 31; 34; 78; 79; 103-105; 126; 127
5	22,887	7	7	3; (10); 15; 17; 24; 26; 28; 30; 35; 38; 59; 80; 128
6	22,865	14	14	(7); 29; 32; 36; 39; 82
7	22,890	19	22	(12); 23; 33; 64; 131
8	23,255	21	22	4; 5; (11); 16; 18; 70; 81; 84
9	23,183	22	22	(8); 83; 109
10	22,970	22	23	(40); 63; 69; 85; 106; 108; 129; 130; 132
11	25,880	33	34	(45); 65; 71; 72; 86; 107; 110; 133-135
12	25,730	43	48	(44); 73; 87-91; 111-113; 136-138
13	26,080	51	59	(42); 74; 92; 93; 114-117; 139; 140
14	25,040	71	71	(46); 75; 94; 95; 98-101; 118; 119; 141-146
15	24,950	74	76	(41); 96; 97; 120-124
16	24,980	77	77	(47); 66-68; 76; 77; 102; 147

*Contents of the modules are identified in Table 8 of the Appendix.

Table 6 -- Results of Second Computer Run (All Modules)*

Trip	Total Weight (lb)	Earliest Delivery (month)	Latest Delivery (month)	Modules and Carriers
1	22,859	0	0	(9); 19; 20; 25; 27; 56; 78; 148A; 150A-156A; 158A-161A; 163A; 164A; 166A; 168A
2	22,847	0	0	1; (6); 21; 31; 34; 169A; 292A; 293A
3	22,840	0	2	(12); 22; 37; 64; 149A; 157A; 165A
4	22,780	2	3	(51); 55; 57-61; 65; 127; 162A; 167A
5	23,787	7	7	4; 5; (10); 14; 15; 17; 24; 26; 28; 30; 38; 128
6	23,651	11	14	3; (7); 32; 35; 36; 39; 81
7	23,507	15	17	(8); 29; 33; 70
8	23,880	18	19	(45); 69; 79; 103-106; 131
9	23,620	19	19	(40); 62; 80; 82; 83; 107; 108; 125; 126; 129; 130
10	24,565	22	22	(11); 18; 23; 109
11	23,670	22	22	2; (13); 16; 84; 85; 170A-173A
12	24,700	40	40	(47); 63; 71; 86; 110; 132; 133; 135; 181A-189A
13	24,600	44	48	(44); 87; 88; 111-113; 134; 136; 192A; 213A; 214A; 263A; 267A
14	24,530	44	49	(53); 72; 114; 115; 138; 190A; 191A; 193A-195A; 212A; 261A; 264A; 273A
15	24,910	54	55	(42); 73; 74; 89-93; 95; 116; 117; 137; 140; 262A
16	24,740	59	60	(52); 66-68; 75; 178A; 179A
17	24,850	60	60	(48); 174A-177A; 180A; 222A; 255A-260A; 265A; 271A
18	24,820	60	71	(46); 94; 229A-254A; 266A
19	24,800	64	66	(49); 139; 141-144; 196A; 215A; 220A; 225A; 227A; 228A; 294A
20	25,100	64	73	(41); 268A-270A; 274A-291A
21	24,900	67	73	(54); 96; 118-122; 226A
22	25,010	74	80	(43); 102; 197A-211A; 216A-219A; 221A; 223A; 224A
23	24,700	77	77	(50); 76; 77; 97-101; 123; 124; 145-147; 272A

*Contents of the modules are identified in tables 8, 9, and 10 of the Appendix.

6000 pounds of "other," nonspecified scientific equipment was, therefore, delivered during the first 22 months of operation of the base.

Table 7 is a listing of arrival times -- at the lunar base -- of some of the major astronomical equipment. For equipment that has been split into several parts, the delivery time given is that of the last part needed to make the equipment complete. Note however, that while partial assembly can commence earlier, operation will realistically start only some time after assembly has been completed.

Discussion

It was mentioned in the Introduction that the mathematical model can be used in two different modes. The numerical data from the two basic computer runs described here must be considered as planning estimates. Before using the model in an operating real-time mode many additional considerations would have to enter. We shall give one simple example.

Table 7 -- Arrival Times of Selected Major Items of Astronomical Equipment

Equipment	Month of Latest Delivery
Meridian Transit Circle	0
Reflector, 10"	2
Coronagraph	3
Radio Astronomy Antenna Net	3
Reflector, 36"	22
Coude Spectrograph	40
Spectroheliograph	49
Solar Telescope	60
Parabolic Radio Disk, 28'	80
Large Reflector, 60"	80

A matching of the launch intervals against pad availability on a three-pad launch complex with a pad-turnaround time of one month would indicate the "ample" feasibility of both runs' launch intervals. But given the number of launch pads actually available, the arrival rate of space vehicles at the pads, the turnaround time of each pad, etc., one could assess whether a planned launch complex can handle the launch schedule on the basis of the intervals indicated by the model's results. One might wish to have one pad ready at all times to deal with emergencies. Should the launch intervals derived by the model not be compatible with the facilities at the launch complex, the parameters of the model could be adjusted to derive a different set of launch intervals that would still adequately support the operations at the base in space. Computation would continue until it was established that there is no compatible schedule of launches for the planned complex, or until a suitable schedule is found.

For the present runs, neither launch failures nor emergencies in space were considered. Work is underway, however, to develop a model that can better consider these and other stochastic aspects of actual space operations.

Considerable research remains before it is possible to determine with accuracy the logistic implications of creating a lunar astronomical research program. All weight estimates would have to be refined, because of their sensitivity in relation to the model. In addition, alternate plans should be analyzed and the conjectural aspects of space operations investigated. On the basis of the two computer runs described, however, it would appear feasible to deliver to the moon all the equipment and instrumentation listed in the Appendix within seven years after the start of a long-term manned lunar-base operation. It further would appear that the cost of the astronomy program is seven additional trips during the eight-year period of operation considered here. The launch intervals involved also seem compatible with a program of resupply of the essentials needed to keep the base in operation and with personnel rotation requirements.

Recognize, however, that we have been considering the delivery of astronomical modules in relative isolation from other scientific equipment, and have examined neither the assembly restraints imposed by the lunar environment nor the number of persons available for construction.

Conclusions

Consider first the example used here to illustrate the capabilities of the mathematical model of the supply support of space operations. Of the equipment called for by the sciences to be placed on the moon for some time to come, that called for by astronomy is probably the bulkiest. One may argue the scientific merits of such an endeavor, but a priori, we were not able to estimate, even remotely, whether a 60-inch telescope on the moon would be a logistically and economically realistic task for this century or for the next.

Though interesting and useful, the numerical results presented in this paper are of secondary significance at this time. The primary importance is the demonstration of a technique that can generate meaningful logistic statements from such diverse input parameters as weight and volume of equipment, capacities of launch vehicles and spacecraft, number of available launch pads, scientific mission objectives, allowable times of unattended storage of expendable goods, and many others. Furthermore, any input can be examined in parametric fashion in order to determine the sensitivity of the whole system to it.

Consider now the implications of having this tool available to the space-mission planner. Hardware and supply requirements, as well as scientific and technical objectives, can be scaled up or down; operations schedules can be extended in time or shortened; mission alternatives can be compared quantitatively, including the comparison of such missions as accomplishing a specific scientific objective by means of a lunar base vs. an orbiting laboratory, by means of manned operations vs. unmanned spacecraft.

We readily conclude that use of the space-base supply model can greatly assist in the integrated mission planning and comparative evaluation of space programs.

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Appendix

Table 8

Base Supply Modules and Logistics Carriers for Initial Two-Year Period of Operations

No.	Modules and Carriers	Weight (lb)	Volume (cu ft)	Month of Earliest Possible Delivery	Month of Latest Possible Delivery
1	Mission Support Equipment	880	25	-11	0
2	Fuel Synthesis Experiment	6900	190	11	22
3	Mission Support Equipment	2760	77	11	22
4	Mission Support Equipment	1460	40	3	14
5	Mission Support Equipment	1650	45	-4	7
(6)	Basic Shelter	19750	(2463)	-11	0
(7)	Basic Shelter	18770	(2463)	3	14
(8)	Basic Shelter	18530	(2463)	11	22
(9)	Logistics Carrier	4100	(3870)	-11	22
(10)	Logistics Carrier	4100	(3870)	-11	22
(11)	Logistics Carrier	4100	(3870)	-11	22
(12)	Logistics Carrier	4100	(3870)	-11	22
(13)	Logistics Carrier	4100	(3870)	-11	22
14	Extended Mobility	1650	516	-4	7
15	Extended Mobility	1650	516	3	14
16	Extended Mobility	1650	516	11	22
17	Basic Lunar Roving Vehicle	3760	1280	3	14
18	Basic Lunar Roving Vehicle	3760	1280	11	22
19	Antenna Set - Lunar Roving Vehicle	120	4	-11	0
20	Basic Lunar Roving Vehicle	3760	1280	-11	0
21	Basic Maintenance Equipment	400	25	-11	0
22	Nuclear Power Unit (100 kW)	12850	285	-4	7
23	Nuclear Power Unit (100 kW)	12850	285	11	22
24	Construction Power Unit	1640	6	-4	7
25	Engineering Equipment - Shielding	1710	72	-9	2
26	Engineering Equipment - Transportation	1460	64	3	14
27	Life Support Supply	2370	51	-2	2
28	Life Support Supply	2370	51	5	12
29	Life Support Supply	2370	51	9	17
30	Life Support Supply	2370	51	2	8
31	Base Substation	500	12	-4	7
32	Antenna Set - Lunar Roving Vehicle	120	4	3	14
33	Antenna Set - Lunar Roving Vehicle	120	4	11	22
34	Fuel Regeneration Unit	520	6	-4	7
35	Basic Maintenance Equipment	400	25	3	14
36	Basic Maintenance Equipment	400	25	11	22
37	Supplemental Maintenance Equipment	600	35	-9	2
38	Supplemental Maintenance Equipment	400	25	3	14
39	Supplemental Maintenance Equipment	400	25	11	22

Table 9

Base Supply Modules and Logistics Carriers for Added Six-Year Period of Operations

No.	Modules and Carriers	Weight (lb)	Volume (cu ft)	Month of Earliest Possible Delivery	Month of Latest Possible Delivery
(40)	Logistics Carrier	4100	(3870)	-11	96
(41)	Logistics Carrier	4100	(3870)	-11	96
(42)	Logistics Carrier	4100	(3870)	-11	96
(43)	Logistics Carrier	4100	(3870)	-11	96
(44)	Logistics Carrier	4100	(3870)	-11	96
(45)	Logistics Carrier	4100	(3870)	-11	96
(46)	Logistics Carrier	4100	(3870)	-11	96
(47)	Logistics Carrier	4100	(3870)	-11	96
(48)	Logistics Carrier	4100	(3870)	-11	96
(49)	Logistics Carrier	4100	(3870)	-11	96
(50)	Logistics Carrier	4100	(3870)	-11	96
(51)	Logistics Carrier	4100	(3870)	-11	96
(52)	Logistics Carrier	4100	(3870)	-11	96
(53)	Logistics Carrier	4100	(3870)	-11	96
(54)	Logistics Carrier	4100	(3870)	-11	96
	Logistics Carrier (not used)	4100	(3870)	-11	96
	Logistics Carrier (not used)	4100	(3870)	-11	96
55	Hydrogen; and Nitrogen	840	189	-7	3
56	Hydrogen; and Nitrogen	840	189	-7	4
57	Hydrogen; and Nitrogen	840	189	-7	5
58	Hydrogen; and Nitrogen	840	189	-7	6
59	Nitrogen	1200	68	-4	17
60	Oxygen	4720	166	0	3
61	Oxygen	4720	166	0	6
62	Oxygen	4720	166	0	41
63	Oxygen	4720	166	0	50
64	Oxygen	4720	166	0	59
65	Oxygen	4720	166	0	68
66	Oxygen	4720	166	0	77
67	Oxygen	4720	166	0	87
68	Oxygen	4720	166	0	96
69	Nitrogen	2480	119	6	23
70	Nitrogen	2480	119	15	31
71	Nitrogen	2480	119	24	40
72	Nitrogen	2480	119	33	49
73	Nitrogen	2480	119	46	58
74	Nitrogen	2480	119	50	67
75	Nitrogen	2480	119	59	76
76	Nitrogen	2480	119	68	85
77	Nitrogen	2480	119	77	93
78	Water Management; Hygiene; and Waste Treatment	795	3	0	19
79	Water Management; Hygiene; and Waste Treatment	795	3	4	24
80	Water Management; Hygiene; and Waste Treatment	795	3	7	27
81	Water Management; Hygiene; and Waste Treatment	795	3	11	30
82	Water Management; Hygiene; and Waste Treatment	795	3	14	33
83	Water Management; Hygiene; and Waste Treatment	795	3	19	38
84	Water Management; Hygiene; and Waste Treatment	795	3	21	40
85	Supplemental Water Management	216	2	22	43
86	Water Management; Hygiene; and Waste Treatment	795	3	26	45
87	Water Management; Hygiene; and Waste Treatment	795	3	29	48
88	Water Management; Hygiene; and Waste Treatment	795	3	32	52
89	Water Management; Hygiene; and Waste Treatment	795	3	36	55

Table 9 -- continued

No.	Modules and Carriers	Weight (lb)	Volume (cu ft)	Month of Earliest Possible Delivery	Month of Latest Possible Delivery
90	Water Management; Hygiene; and Waste Treatment	795	3	39	59
91	Water Management; Hygiene; and Waste Treatment	795	3	43	62
92	Water Management; Hygiene; and Waste Treatment	795	3	46	65
93	Water Management; Hygiene; and Waste Treatment	795	3	49	68
94	Supplemental Water Management	216	2	51	71
95	Water Management; Hygiene; and Waste Treatment	795	3	54	73
96	Water Management; Hygiene; and Waste Treatment	795	3	57	76
97	Water Management; Hygiene; and Waste Treatment	795	3	61	80
98	Supplemental Hygiene	140	1	62	83
99	Water Management; Hygiene; and Waste Treatment	795	3	65	84
100	Water Management; Hygiene; and Waste Treatment	795	3	68	87
101	Water Management; Hygiene; and Waste Treatment	795	3	71	90
102	Supplemental Water Management; and Supplemental Waste Treatment	655	5	74	94
103	Food	3845	28	0	19
104	Food	3845	28	4	24
105	Food	3845	28	12	27
106	Food	3845	28	11	31
107	Food	3845	28	15	34
108	Food	3845	28	18	38
109	Food	3845	28	22	42
110	Food	3845	28	25	45
111	Food	3845	28	29	49
112	Food	3845	28	32	52
113	Food	3845	28	36	56
114	Food	3845	28	39	59
115	Food	3845	28	43	63
116	Food	3845	28	46	66
117	Food	3845	28	50	70
118	Food	3845	28	53	73
119	Food	3845	28	57	77
120	Food	3845	28	60	80
121	Food	3845	28	64	84
122	Food	3845	28	67	87
123	Food	3845	28	71	91
124	Food	3845	28	74	94
125	Clothing	1101	8	0	19
126	Clothing	1101	8	4	24
127	Lithium Hydroxide	148	1	2	21
128	Clothing; and Lithium Hydroxide	1249	8	7	27
129	Clothing; and Lithium Hydroxide	1249	8	12	31
130	Clothing; and Lithium Hydroxide	1249	8	16	35
131	Clothing	1101	8	18	38
132	Clothing; and Lithium Hydroxide	1249	8	22	42
133	Clothing; and Lithium Hydroxide	1249	8	26	45
134	Clothing	1101	8	29	49
135	Clothing; and Lithium Hydroxide	1249	8	32	52
136	Clothing; and Lithium Hydroxide	1249	8	36	56
137	Clothing	1101	8	39	59
138	Clothing; and Lithium Hydroxide	1249	8	43	62
139	Clothing; and Lithium Hydroxide	1249	8	46	66
140	Clothing; and Lithium Hydroxide	1249	8	51	70
141	Clothing	1101	8	53	73
142	Clothing; and Lithium Hydroxide	1249	8	57	77
143	Clothing; and Lithium Hydroxide	1249	8	60	80
144	Clothing	1101	8	64	84
145	Clothing; and Lithium Hydroxide	1249	8	67	86
146	Clothing; and Lithium Hydroxide	1249	8	71	91
147	Clothing	1101	8	74	94

Table 10

Astronomical Modules Containing Scientific Equipment, Instrumentation, and Supplies

No.	Astronomy Modules	Weight (lb)	Volume (cu ft)	Month of Earliest Possible Delivery	Month of Latest Possible Delivery
148A	Semiautomatic Telescope, 6" (with finder telescope) QUESTAR Telescope Chronometers Occultation Devices Filters (box) Camera Astronomical Plates (boxes) Spectroscope (attachment) Recording Photometer Data Storage Unit	200	45	-11	24
149A	Reflector Telescope (Cassegrain 10")	400	40	-11	24
150A	Meridian Transit Circle and 3" refractor (without pier)	1000	60	-11	24
151A	X-ray Telescope Darkroom (old LEM?) Visual Micrometer Visual Photometer Thermocouples Monochromatic Filters	165	63	-11	24
152A	Spectrograph	400	45	-11	24
153A	Darkroom Supplies (including chemicals; water; plate cutter; pans; etc.)	1000	48	-11	24
154A	Schmidt Camera (Part 1 of 2)	1000	54	-11	24
155A	Schmidt Camera (Part 2 of 2)	1000	54	-11	24
156A	Coronograph	800	50	-11	24
157A	Radio Astronomy Antenna Net (Part 1 of 3)	100	333	-11	24
158A	Radio Astronomy Antenna Net (Part 2 of 3)	100	333	-11	36
159A	Radio Astronomy Antenna Net (Part 3 of 3)	100	333	-11	36
160A	Micro-Densitometer (Part 1 of 2)	750	54	0	36
161A	Micro-Densitometer (Part 2 of 2)	750	54	0	36
162A	Blink Comparator	300	27	0	36
163A	Measuring Engine	100	2	0	36
164A	Linear Comparator	400	27	0	36
165A	Machine Shop	1000	31	0	36
166A	Recording Photoelectric Photometer	400	27	0	36
167A	Telescope Accessories (Part 1 of 2)	300	27	0	36
168A	Telescope Accessories (Part 2 of 2)	300	27	0	36
169A	Image Converters	250	27	0	36
170A	Polarimeter	150	6	0	36
171A	Infrared Spectrometer	200	36	0	36
172A	Reflector, 36" (Part 1 of 2)	3000	648	0	35
173A	Reflector, 36" (Part 2 of 2)	3000	648	0	35
174A	Astrograph, 10" (Part 1 of 2)	2000	108	0	36
175A	Astrograph, 10" (Part 2 of 2)	2000	108	0	36
176A	Solar Telescope, 40" (Part 1 of 4)	2500	648	36	60
177A	Solar Telescope, 40" (Part 2 of 4)	2500	648	36	60
178A	Solar Telescope, 40" (Part 3 of 4)	2500	648	36	60
179A	Solar Telescope, 40" (Part 4 of 4)	2500	648	36	60
180A	Infrared Telescope (Part 1 of 3)	2000	108	24	60
181A	Infrared Telescope (Part 2 of 3)	2000	108	24	60
182A	Infrared Telescope (Part 3 of 3)	2000	108	24	60
183A	Coude Spectrograph Attachments (Part 1 of 4)	500	54	24	60
184A	Coude Spectrograph Attachments (Part 2 of 4)	500	54	24	60
185A	Coude Spectrograph Attachments (Part 3 of 4)	500	54	24	60
186A	Coude Spectrograph Attachments (Part 4 of 4)	500	54	24	60
187A	Spectroheliograph (Part 1 of 4)	500	54	24	60
188A	Spectroheliograph (Part 2 of 4)	500	54	24	60
189A	Spectroheliograph (Part 3 of 4)	500	54	24	60
190A	Spectroheliograph (Part 4 of 4)	500	54	24	60

Table 10 -- continued

No.	Astronomy Modules	Weight (lb)	Volume (cu ft)	Month of Earliest Possible Delivery	Month of Latest Possible Delivery
191A through 215A	Parabolic Radio Disk, 28' (25 parts)	1000 (each)	54 (each)	40 (all)	80 (all)
216A	Large Reflector, 60" (Primary Optics)	10000	75	60	96
217A through 256A	Large Reflector, 60" (40 parts)	750 (each)	54 (each)	60 (all)	96 (all)
257A	Expendable Supplies	1000	54	34	60
258A	Expendable Supplies	1000	54	34	61
259A	Expendable Supplies	1000	54	34	62
260A	Expendable Supplies	1000	54	34	63
261A	Expendable Supplies	1000	54	34	64
262A	Expendable Supplies	1000	54	34	65
263A	Expendable Supplies	1000	54	34	66
264A	Expendable Supplies	1000	54	34	67
265A	Expendable Supplies	1000	54	34	68
266A	Expendable Supplies	1000	54	44	69
267A	Expendable Supplies	1000	54	44	70
268A	Expendable Supplies	1000	54	44	71
269A	Expendable Supplies	1000	54	44	72
270A	Expendable Supplies	1000	54	44	73
271A	Expendable Supplies	1000	54	44	74
272A	Expendable Supplies	1000	54	44	75
273A	Expendable Supplies	1000	54	44	76
274A	Expendable Supplies	1000	54	44	77
275A	Expendable Supplies	1000	54	44	78
276A	Expendable Supplies	1000	54	44	79
277A	Expendable Supplies	1000	54	54	80
278A	Expendable Supplies	1000	54	54	81
279A	Expendable Supplies	1000	54	54	82
280A	Expendable Supplies	1000	54	54	83
281A	Expendable Supplies	1000	54	54	84
282A	Expendable Supplies	1000	54	54	85
283A	Expendable Supplies	1000	54	54	86
284A	Expendable Supplies	1000	54	54	87
285A	Expendable Supplies	1000	54	54	88
286A	Expendable Supplies	1000	54	54	89
287A	Expendable Supplies	1000	54	64	90
288A	Expendable Supplies	1000	54	64	91
289A	Expendable Supplies	1000	54	64	92
290A	Expendable Supplies	1000	54	64	93
291A	Expendable Supplies	1000	54	64	94
292A	Expendable Supplies	1000	54	64	95
293A	Expendable Supplies	1000	54	64	96
294A	Expendable Supplies	1000	54	64	96

Summary

In an earlier study, a mathematical model was described that can be used to evaluate various aspects of the logistics supply support of space operations. The present study utilizes this model to investigate the implications of superimposing a set of demanding scientific requirements on an existing space base support plan. An illustrative example demonstrates the flexibility and usefulness of the model as a tool for integrated space-mission planning.

First, a scenario is developed for a lunar astronomical research program in sufficient detail to fulfill the input requirements of the model. The resulting scientific requirements are described in terms of the equipment and instrumentation desired in a temporal sequence of gradually increasing demands that culminates in the establishment of an astronomical observatory on the moon.

These requirements then are superimposed on a supply report system that provides for the establishment and operation of a manned lunar base over an eight-year period. Detailed input parameters consider such aspects as capacities of launch vehicles and spacecraft, number of launch pads and pad turnaround times, scientific mission objectives, and allowable times for unattended storage of expendable goods, to name a few.

The numerical results from two computer runs determined the necessary delivery schedules and provided an indication of the logistic cost of the postulated mission. For the specific astronomical example investigated, the results indicated that a lunar astronomical research program that culminates in the construction of a lunar-based observatory is logistically feasible. Further, such an observatory with sizable equipment could be established -- without any unrealistic logistic requirements -- within the next decades rather than during the next century.

However, these numerical results are of secondary significance at this time. The primary importance of the study is the demonstration of a technique that permits the quantitative comparison of the logistical aspects of alternative space missions where many interrelated input parameters can be examined in parametric fashion to determine the sensitivity of the system to each. Possible future applications include the quantitative analysis of such alternatives as reaching a specific technical objective by means of a lunar base or with an orbiting laboratory, by means of manned operations or with unmanned spacecraft.

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