THE CONCEPT OF THE TIME INTERVAL MEASUREMENT AND CONTROL CIRCUITRY FOR THE LUNAR RANGING EXPERIMENT: A HISTORY

by

S. K. POULTNEY

Technical Report No. 70-68

December 1969

UNIVERSITY OF MARYLAND
DEPARTMENT OF PHYSICS AND ASTRONOMY
COLLEGE PARK, MARYLAND

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University of Maryland

Department of Physics & Astronomy

College Park, Maryland

Abstract

The concept of the time interval measurement and control circuitry for the Lunar Ranging Experiment prior to January 1969 is here recorded. The suggested components of the system are also given. The present electronics at the McDonald Observatory station were developed directly from this concept and includes many of the suggested components. Some later documentation of concept and components is included for completeness. Reference to University of Maryland, Department of Physics and Astronomy, Technical Report #70-049 by C. A. Steggerda is essential for an understanding of the present McDonald electronics.

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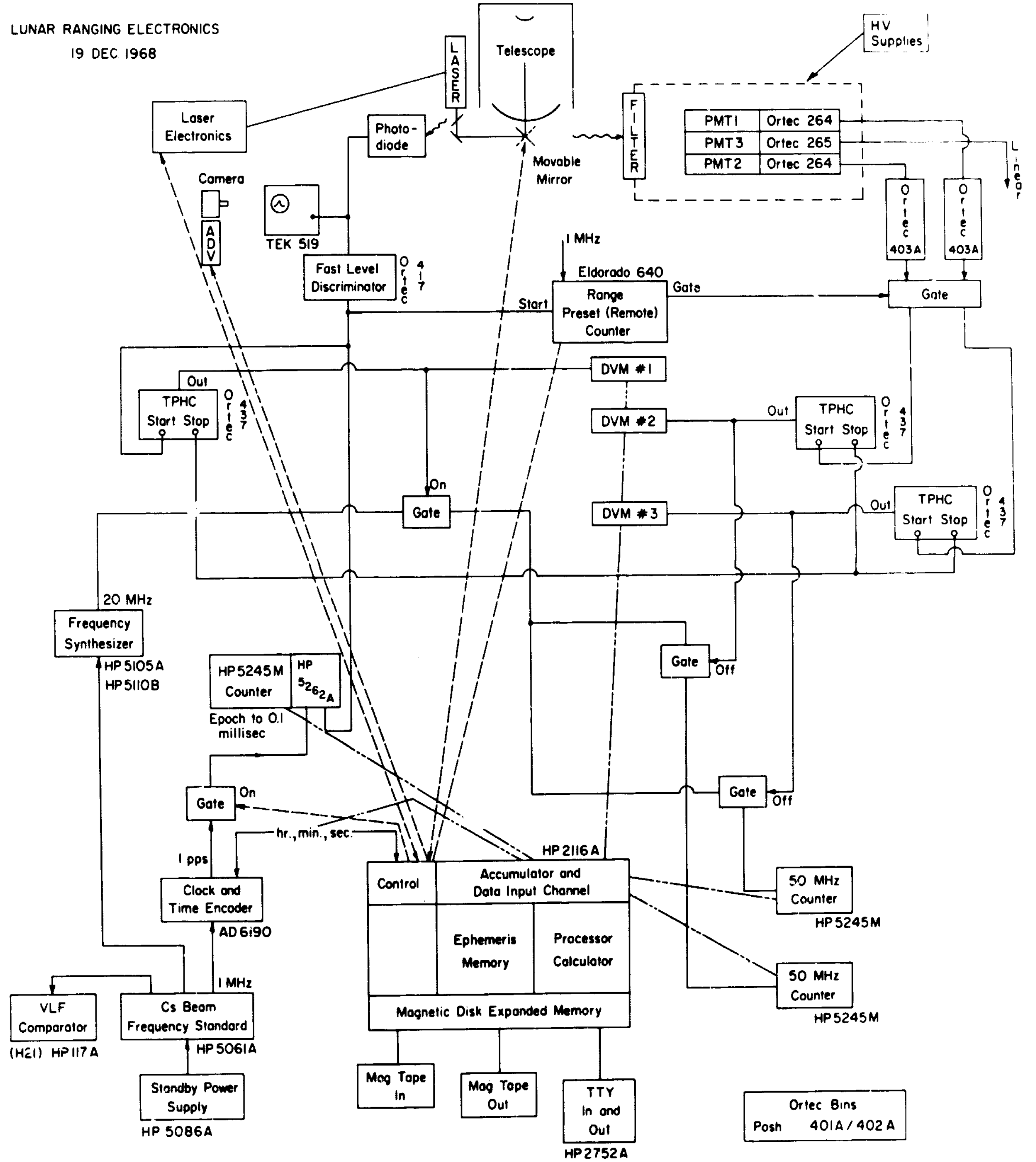
Acknowledgments

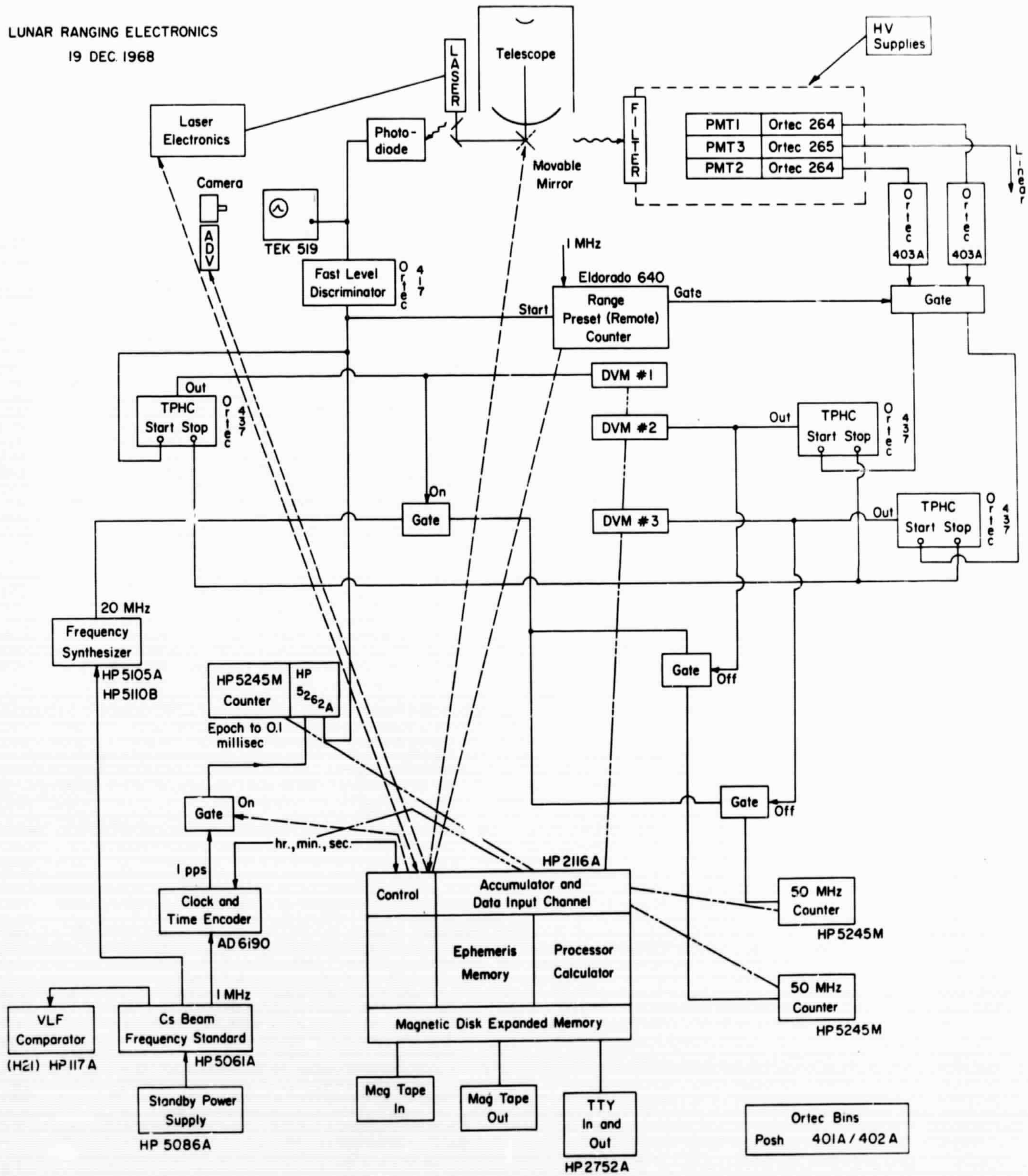
The concept of the electronics for the Lunar Ranging Experiment was primarily the responsibility of the author. However, extensive discussion with Robert Detenbeck in the early stages and with Douglas Currie in the later stages is acknowledged.

The realization of the concept was the responsibility of the author and C. A. Steggerda. After the early stage of writing equipment specifications and selecting components, however, the responsibility was primarily that of C. A. Steggerda whose many contributions are well-documented in his technical report (University of Maryland Tech Report #70-049). Without these many contributions, the Lunar Ranging electronics could not have been realized to either the extent or the deadline achieved.

SECTION II

Lunar Ranging Electronics Circuit Diagram (December 19, 1968)


LUNAR RANGING ELECTRONICS
19 DEC 1968
LASER
Telescope
HV Supplies
Laser Electronics
Photo-diode
Movable Mirror
FILTER
PMT1
Ortec 264
PMT3
Ortec 265
PMT2
Ortec 264
Camera
ADV
TEK 519
Ortec 403A
Ortec 403A
1 MHz
Eldorado 640
Fast Level Discriminator
Ortec 417
Start
Range Preset (Remote) Counter
Gate
Gate
DVM #1
Out
TPHC Start Stop
Ortec 437
DVM #2
On
Gate
DVM #3
20 MHz
Frequency Synthesizer
HP 5105A
HP 5110B
HP 5245M Counter
HP 5262A
Epoch to 0.1 millisec
Gate
Off
Gate
On
Off
hr., min., sec.
1 pps
HP 2116A
Control
Accumulator and Data Input Channel
Clock and Time Encoder
AD 6190
Ephemeris Memory
Processor Calculator
50 MHz Counter
HP 5245M
1 MHz
VLF Comparator
Cs Beam Frequency Standard
Magnetic Disk Expanded Memory
(H21) HP 117A
HP 5061A
Standby Power Supply
HP 5086A
Mag Tape In
Mag Tape Out
TTY In and Out
HP 2752A
Ortec Bins
Posh 401A / 402A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Eldorado 640
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Gate
DVM #1
DVM #2
DVM #3
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TPHC Start Stop
Ortec 437
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TPHC Start Stop
Ortec 437
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Epoch to 0.1 millisec
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Mag Tape Out
TTY In and Out
HP 2752A
Ortec Bins
Posh 401A / 402A

SECTION III.

List of Ground Station Electronics

(Letter to W. Carrion-December 17, 1968)

December 17, 1968

Mr. Walter Carrion
Code 524
Goddard Space Flight Center
Greenbelt, Maryland 20771

Dear Walt:

Here follows a partial list of Ground Station electronics with the name of its function and a suggested model number. Some items have no suggested model number as of yet.

1. Cesium Beam Frequency Standard and Clock

   Hewlet-Packard E20-5061 A

   a. Cesium Beam Standard
      HP 5061 A — $14,800

   b. Time Standard
      Option 01 — 1,500

   c. Standby Power Supply
      HP 5086 A — 2,750

2. VLF Comparator
   HP H21-117 A — 1,575

3. Time Encoder
   Model ?
   Convert HP Time Standard Signal (1pps) to (Hour, Minutes, Seconds) allowing both BCD output and visual display

4. Electronic Counter (50 MHz, versatile)
   HP 5245 M — 2,750

5. Time Interval Plug-in Unit
   HP 5262 A — 250
   With HP 5245 M this unit measures laser pulse output time to the required 0.1 millisecond BCD output.

6. Frequency Synthesizer
   HP 5105 A — 9,150
   HP 5110 B (Option 02) — 4,475
   Supplies master frequency for range measurement.

7. Electronic Counters (2 each) $2,750
   HP 5245 M
   (50 MHz, versatile, BCD output)
   Counts range of moon

8. Preset Counter
   Model ?
   Allows gating-off of detector until a selected time. Must allow N to be remotely preset. N must range from 1 to 20,000,000.

   External frequency generator will be available.

9. Auxiliary Counter Plug-ins

   a. Prescaler Plug-in (135 MHz)
      HP 5252 A 685

   b. Digital Voltmeter Plug-in
      HP 5265 A 575

10. Pulse Generator
    HP 8002 A 700
    Rack-mounted, test generator

11. Test Oscilloscope
    Tek R-54 Mod 163 D 2,735
    Rack-mounted
    Accessories (Probe, C-40 Camera, Cart) 875

12. Modular System Bin and Power Supply (2 each)
    Ortec 401A/402A
    (with ac line filter) 680 each

13. Fast Discriminator (2 each)
    Ortec 417 400 each

14. Time-to-Pulse Height Converter
    Ortec 437 725
    In conjunction with 417, does Vernier timing of output laser pulse.

15. 3 KV Regulated DC High Voltage Supply (2 each)
    Keithley 246 450 each

16. 6 KV Regulated DC High Voltage Supply
    Fluke 408 B 665

17. Photomultipliers (3 each)
    Model ?
    Type RCA 8575 with selected S-20 photocathode with 4% quantum efficiency at 6943 Å, low noise,

and new dynode material. Probably will be a special order.

18. Time Pick-Off Control (2 each) Ortec 403 A — $ 255 each

19. Photomultipliers Timing Base (2 each) Ortec 264 — 550 each

20. Photomultiplier Base Ortec 265 — 205

21. Linear Gate Ortec 426 — 225

22. Time-to-Pulse-Height-Converter (2 each) Ortec 437 — 725 each

Items 15 to 22 allow the Vernier timing of the return laser pulse and the logic signals that turn off the counters recording the range. Digital voltmeters to record the TPHC outputs have not yet been selected (probably HP to match computer). The logic units (e.g. linear gates) have also not yet been selected.

23. Additional Test Equipment (On-site calibration of PMTS and TPHC)

   a. Multi Channel Analyzer (w/printer) Northern Scientific NS 601/NS/102 — $5,590.50

   b. Nanosecond Delay (2 each) Ortec 425 — 140 each

   c. Nanosecond Light Pulser
      Model ?
      See T. Johnson: Current pulses plus at least three outputs and three diodes.

Also not listed are the control computer, its accessory devices, control circuits, filter monitor circuits, filter adjust circuits, and other control devices.

Yours truly,

Sherman K. Poultney

Sherman K. Poultney
Assistant Professor of Physics

SKP:mm

cc: D. Currie T. Johnson
C. O. Alley P. Minott

SECTION IV.

Concept of Lunar Ranging Electronics

(Letter to P. McCormick-December 5, 1968)

December 5, 1967

Dr. Paul McCormick
The University of Michigan
2062 Vineyard Street
P. O. Box 965
Wailuku, Maui, Hawaii 96793

Dear Mac:

1. We've begun sketching out the details of the electronics for the lunar experiment. All the necessary parts appear to be commercially available. The equipment to be used to establish that the digitized-return faithfully represents a photon arrival time (see Tech. Rep. 725) has arrived and will soon be tested. This same equipment is also capable of doing both coarse and fine-ranging under conditions outlined below. Our present conception of the electronics is given below. I will keep sending you more-detailed reports as we generate them.

2. Conception of Electronics. Assuming that the Ortec Time-Pickoff Method (e.g. Ortec 264 and Ortec 403A) works such as to yield a one-shot uncertainty in arrival time of 0.7 nsec and a sufficient number of photomultipliers is used (probably three or less) to allow detection of no more than one photoelectron in each channel per shot, one can do the vernier-ranging by starting a Time-to-Pulse Height Converter (e.g. Ortec 437 or see Rev. Sci. Inst. 38, 1220, Sept. 1967) with a range-gate start pulse from a preset range counter (i.e. preset with predicted range at time of shot) and by stopping the TPHC in each channel when the return arrives in that channel. The Ortec TPHC has a precision of 0.01% of the time range set and has 15 time ranges from 50 nsec to 80 nsec full scale. Its stability and linearity could be monitored between shots if desired.

The TPHC output is an analog output, but is compatible with all standard multi-channel analyzer inputs (or other A to D converters). The output of each channel's analyzer will be read into magnetic disk memory along with the TPHC range setting and preset range after each shot.

Also to be recorded on the magnetic disk for each shot are the UT of a master control signal to an accuracy to be specified, the departure time of the outgoing laser pulse, the laser-pulse energy, and if need be, information about the laser-pulse shape. The departure time of the laser-pulse could be determined by adding one extra channel to the detector, scattering some of the outgoing laser light into this channel (also a check of filter-laser overlap), and stopping that channel's TPHC which had been started by the same master control signal which started the preset range counter. The pulse-height of the laser pulse could be determined by sending the linear PMT signal to another multi-channel analyzer. If for some unexpected reason the laser pulse should change its shape erratically, a more sophisticated pulse-shape monitor would have to be used.

We have now recorded on a magnetic disk for rapid retrieval all the information necessary to specify the range to the moon to 10 nsec <u>for one shot</u> and to 0.7 nsec for a <u>sufficient</u> number of shots. A firing sequence would be as follows. The control-computer will initiate the sequence when the retroreflector is in the detector's field of view. When the laser is ready to fire, the control computer questions the stable clock for the U.T., selects the correct range for the U.T. from the stored, precalculated ephemeris, sets the range in the preset counter, selects the correct range-gate, fires the laser, and reads the U.T. of the initiation pulse (to an accuracy to be specified later). The stable clock need only be a 100 mhz clock which is periodically checked against the Naval Observatory clock on Maui and which has a short-term stability of one part in 10^{10}. The discriminator (e.g. Ortec 417) of each preset counter will certainly trigger at a given pulse-height with a walk of less than 0.5 nsec for the standard output pulse of the clock. The preset itself is discussed below.

3. Range-Gating Mode

Each shot produces one, several, or no TPHC entries in the disk memory. These entries may be examined immediately, stored, grouped with other shot entires, etc. Noise rates could be determined by starting the TPHC between shots and recording the noise entries. Note that this TPHC method can be used in place of the original coarse-ranging scheme only when the noise rate is small (e.g. ranging to dark portion of lunar disk). If the noise rate were not small, one would probably want to find the target as discussed in the original coarse-ranging scheme because more efficient use is made of each shot. After finding the target, one would switch to the TPHC fine-ranging. The establishing of confidence levels would proceed as has been previously discussed. Several returns per shot would, of course, help matters considerably as does locating at range minimum. The suggestion of extracting several Q-chop pulses (multipulses) during one laser pump cycle is enticing, but will probably not be practical because the data from the first multipulse may not be processed by the time the second goes out (1μsec). Since a number of shots may be necessary to determine the desired confidence level, the superposition of shot entries must be discussed. This discussion will appear under the subject of Range Ephemeris. Note that use of multipulses would somewhat alleviate the problem of superposition of pulses of different ranges or of finding the target in a spatial search mode.

4. Spatial Search Mode

The precision of tracking of the target in angle will depend on the particular method used. Off-set from a star is one. Off-set from surface features is another. The former is diffucult because of the wide field of view required. The latter may become difficult during certain phases of the moon (e.g. lack of shadows during local "noon"). Poor tracking implies loss of information, but does not mean loss of range accuracy Spatial search modes would help locate the target if it is momentarily lost in angle. However, if enough returns are lost, one may never locate the target in range-time, in spite of spatial search modes, depending on the rate of range change.

5. Preset Precision and Accuracy

The construction or availability of the preset unit which must count 2.5 sec to an accuracy of 10μsec and start and stop with a precision of less than a nanosecond has yet to be looked into.

6. Computer Size and Data Analysis

The computer must have sufficient memory to store the working Range Ephemeris (at least one day's entries). It must be able to control the entire operation except angle tracking. This control includes making the laser ready, setting preset counters, setting range gates, executing the shot, blocking the telescope observer from the laser flash, and clearing the settings. It must be able to read and store the entires, calculate confidence levels and feed back confidence levels to range-gate settings.

It may be required to analyze the data on site. However, analysis will probably be done at the University of Maryland. This analysis would be primarily a comparison of expected range with observed range; including laser pulse shape and other corrections. The data could be transferred by air on magnetic tape.

No computer has been selected yet, but one like a Data 620 I is a candidate. It has an expandable memory and looks about the size and speed needed.

7. Range Ephemeris

A master ephemeris could be calcualted for the weekly lunar passage based on Brown's theory for the main problem of lunar motion and on Eckhardt's solutions and then stored in computer memory for later use. The number of entries needed will depend on the number of shots desired for each passage (e.g. 200 every hour) multiplied by a factor that depends on the rate of change of rate and the range-gate selected. A more flexible method would be one that used a coarse range ephemeris supplemented by a range-rate (or range-acceleration) ephemeris. The control computer would then interpolate the expected range for each shot or each group of shots. The entries needed for this latter method can be estimated by examining the expansion of the receiver-retroreflector distance in terms of the sixteen parameters involved (see Bender, Supplement 2). The initial range-gate and obtainable parameter accuracies are also estimated from such an expansion. These three range problems are somewhat interdependent and so will be discussed in turn. That is, there is no sense in requiring range interpolations finer than either range gate intervals or persent range uncertainties. An accurate record of the time of departure can always be used to calculate a new expected range back at Maryland. All that is required is that a return is located within the range gate and timed to sufficient accuracy.

First, let us consider range and range-rate assuming there are no uncertainties. This information will allow us to estimate the size of the range ephemeris required and to discuss the problem of super position of shots. Julian (AFCRL 66-503) has followed the expansion approach and finds that, to an accuracy of ± 15 m/sec, the range rate is given by a monthly term due to the lunar orbit and a daily term due to earth rotation. The latter term dominates because of its larger amplitude and because the orbital contribution varies little during any one daily passage. The range rate is approximately linear with time for times before and after minimum range of less than two hours with a maximum of $|200|$ m/sec. The range "acceleration" is therefore 100 $\frac{\text{m/sec}}{\text{hr}}$. Use of the acceleration to calculate range rate and range is indicated within the above time limits. In the same time, the range thus varies quadratically with the time with a maximum of 700 km. Recall that the fine-ranging gate could be as long as 10 μsec (i.e. 1.5 km) for low noise rates. This means an updating of range about fifteen times during a four hour lunar passage. At higher noise rates, the range-gate must be narrower and the number of up-dating increases proportionally.

The initial uncertainty in range is expected to be about 300 m which is due to a 200 m uncertainty in earth-moon distance, a 200 m uncertainty in lunar radius, and a 20 m uncertainty in earth radius. Thus, an initial range gate of 10 μsec is more than sufficient to locate the reflector in range-time and measure its range to the desired accuracy (1 nsec). The working range-gate will be entirely determined by noise rates.

On this basis (i.e. location of reflector and recording departure and arrival times), one need never feed the new parameters calculated by boot-strapping back into the working ephemeris. This is all to the good since the output of new parameters may take a long time.

The location of the reflector which depends upon a confidence level (hence superposition of shots, hence range rate <u>and</u> noise rate) may be another matter. Assume a shot is fired every three seconds and twenty shots are needed to be sure the reflector is located. Near minimum range, the corresponding range-rate is about 2 m/sec and the range change is 120 m. This means that coarse range-gate intervals of no less than 20 nsec can be used to superpose shots without range up-dating at each shot. Two hours before or after minimum range, the minimum coarse range-gate would be 200 nsec with an updating at the beginning of the twenty shot interval. If one can only locate the target at minimum range due to noise, one can use only one-half of a lunar passage. Tracking in range time to the precision of the noise-determined range gate would alleviate all these location problems.

8. I will write about the items that were skimmed over when I get a chance to think about them. Right now I want to finish the precision timing

study. Using the PEK light pulser electrical trigger to start the TPHC and the light signal as seen by a 56TVP (operating at high output levels) to stop the TPHC, I see the quoted 2 nsec jitter of the 56TVP. The measurement is of the leading edge type and I am anxious to try the fast-crossover discriminator with the RCA 8575, first at high output levels, then single photoelectrons. (By the way, one can see the electron travel time in the PMT and its dependence on accelerating voltage - 30 nsec and 0.1 $^{V}/c$). From there, I would like to measure the travel time of the 2 nsec light pulse over a distance of about six meters (18 nsec) to the accuracy of the circuitry. If the accuracy of the circuitry is less than 1 nsec or the light pulse is lengthened, we would have the answer to any doubters of our use of 10 nsec laser pulses to measure to 1 nsec. In lieu of a multi-channel analyzer, I am using an oscilloscope and a differential discriminator. I have also designed a quick-connect, mini-light-tight box to couple PMT and PEK light. It also has provision for quick changes of ND and spectral filters.

9. Dr. Alley just recently asked me when I would like to visit you in Hawaii. I told him after the precise timing work was done and the other electronics is better tied down.

10. Doug Currie thought that the illumination of Surveyor would help solve your bore-sighting problem and then thought illumination of Vela would help even more.

Yours truly,

S. K. Poultney
Assistant Professor

cc: C. O. Alley
D. Currie
R. Detenbeck

SKP:jlb

SECTION V.

Timing and Signal Processing

(with R. Detenbeck, Second Supplement of Maryland Proposal to NASA)

January 9, 1967

E. Timing and Signal Processing by S. K. Poultney and R. W. Detenbeck

Reasonable suggestions based on our prior experience with similar problems are given below for the timing and Signal-Processing aspects of ranging to the moon. A more-detailed design, assembly, and testing will require additional funding.

1. Photomultiplier Tube

A number of photomultiplier tubes are available with sensitivity sufficient to produce an output corresponding to the single-photoelectron expected at the photocathode. This output pulse can be as narrow as two nanoseconds (e.g. Amperex XP1210) and is usually of reasonably standard shape. The amplitude will not be standard due to the gain spread for the amplification of one photoelectron from the cathode, but will be distributed in a statistically determinable manner. There will also be a spread in the transit times which will produce an uncertainty in the arrival time of the signal, but again in a statistically-determinable manner.*

The tube dark-noise has a significantly different pulse-height spectrum so that only a small fraction of the noise pulses will produce outputs as large as a single-photoelectron at the cathode. Sufficient care in the manufacture of the tube and cooling to low temperatures (e.g. dry-ice temperature) will greatly

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* R. Tusting, Q. Kerns, and H. Knudsen
"Photomultiplier Single-Electron Statistics"
IEEE Trans.Nuc.Sci.9, 118 (1962)

M. Bertolaccini and S. Cova
"Amplitude Distribution of Photomultiplier Single Electron Response"
Energia Nucl. 10, 259 (May 1963)

D. Scarl
"Measurement of Photon Time-of-Arrival Distribution in Partially Coherent Light"
Phys.Rev.Letters 17, 663 (1966)

decrease the absolute dark-noise rate. In fact, all the detection and signal processing equipment should probably be temperature-controlled. The tube should also have as small a photocathode as will receive the return signal, in order to reduce thermionic emission.

It will be best to use the tube with the highest gain since photomultipliers are their own best preamplifiers; although for a given tube one must maximize $\frac{S}{N}$ ratio because dark current increases rapidly at H.V. If preamplifiers are needed, a number are available (e.g. the EG&G Pre-amplifier).

2. Pulse-Processing Circuits

It will be found convenient to provide several choices for processing the output pulse of the photomultiplier.

For the coarse range-gating (described below), the pulses are best processed in a discriminator (e.g. the EG&G Discriminator) which accepts pulses above a certain pulse-height and converts each to a standard pulse. These pulses then proceed to the logic and computer for "post-detection" correlation. One could also process the output pulses of the tube with a family of discriminators set for a range of pulse-heights. This information could be used in a "pre-detection" correlation manner to supplement the "post-detection" correlation. However, unlike the tube, the discriminators are non-linear devices which have dead-times. Therefore, if several single-photoelectron are closely-spaced, only the initial pulse would be available for use. Thus the single-photoelectron return (for a broad laser pulse) is not so great a disadvantage (at least for the coarse range-gating) as might first be thought. The total return for each laser pulse will, of course, be available for the vernier ranging (as described later).

For the vernier ranging, the tube output pulse will be used directly. It may be necessary here to use a linear fanout circuit to provide strictly analog output signals to a number of other circuits. A direct pulse may also be required for display on an oscilloscope.

3. Coarse-Range-Gate Logic and Search Sub-Program

It is planned to have a computer in control of the transmitter and receiver pointing. This computer will predict the total range for a particular time which will be used to set the gross delay as described below. It is expected that the range will be known to at least a 1/3 kilometer (1000 nanoseconds) at the start of the experiment and to an increasing degree of precision (and accuracy) as the experiment progresses. The range-gating procedure must thus, at first, narrow down from this 1000 nanoseconds range-gate to a much smaller range-gate interval. Table I gives a measure of the confidence that the signal has been located in a certain range-gate interval as a function of the range-gate interval size and number of firings. One could choose to search the larger range-gate interval with a narrow gate interval. However, to make the most efficient (and fastest) use of the information returning, it is best to record the entire range-gate interval in suitable sub-units and then have a computer sub-program scan the record. If the corner-reflector is located to the desired confidence level on that firing, the sub-program will order the logic to narrow the range-gate (or else the sub-unit) and locate the corner-reflector in one of those sub-units, etc. If the corner reflector is not located to the desired confidence level, the sub-program will allow the radar to continue firing. A spatial search-pattern may also have to be programmed.

The minimum-size sub-unit will probably be determined by the speed of that portion of the computer that would have to record the total amount of information in a particular range-gate. To range to one nanosecond precision, one would need 1 GHZ storage that would be read by a slower computer in the intervals. We here choose a sub-unit of 50 nanoseconds and do vernier ranging by an alternate technique discussed below.

The division of the signal in the range-gate into sub-units will be done as follows. A master clock of 100 MHZ will be used as a time marker by sending its output through a very fast tunnel diode circuit. In this manner, very narrow pulses (1% of clock) will be obtained at a 100 HMZ rate. This time-marker signal will time the Logic so that on each firing the Logic would collect signal-pulses in a 100 mc scaler and dump the accumulation of returns for each range-gate sub-interval (multiple of ten nanoseconds) into the computer memory. It is this record that the computer sub-program examines after each firing. The logic responds to the computer requests by changing (or maintaining) the sub-unit interval for the next firing. (If a 1 GHZ computer is used for the whole analysis, a 1 GHZ clock and 1 GHZ logic would need to be developed).

4. Vernier Gating and Net-Pulse Centroid Determination

The vernier gating and net-pulse centroid determination will determine the arrival time to a precision of 0.3 to 1.0 nanoseconds depending on the number of returns available. This is a statistical result and also depends on the tracking precision. The vernier gating and net-pulse centroid determination could be done using a special sampling scope that may be developed within the year. Once the minimum-size range-gate is located, the photomultiplier to be signal is sent directly (through a fanout) to the special dual-beam scope possessing a family of sampling units. The initial time-marking pulse of the minimum-size range-interval would trigger the oscilloscope and the first bank of the family of sampling units. The family of sampling units might contain a bank of ten sampling units for each time-mark unit. Thus, the first bank would be set with internal delays of one nanosecond between each unit. Each bank could sample one after the other automatically or under command of the time marking pulses. The net-result of one sweep of the range-gate interval (one firing) would be a histogram of the received signal stored in the sampling scope in intervals of one nanosecond. This stored-histogram should be read into the computer memory (by digitizing the stored output of the sampling units). The histogram, for each firing should be kept separate so that they can later be analyzed separately if necessary. The system may then be activated until suitable statistics are obtained to determine the net-pulse (added histograms) centroid to one nanosecond. The net-pulse will, of course, be spread over ten nanosecond due to the time-width of the laster output-pulse.*

Vernier timing will be accomplished by means of tagged time markers which are displayed on the other beam of the sampling-scope. The time markers may be tagged by suitable modulation which begins at the start of the minimum-size range-gate (or other time).

5. Range Accuracy and Delay

The range accuracy and setting the correct delay are potentially the most troublesome aspects of the ranging. One possible method of measuring the range accurately would make use of the tagged time-markers in the vernier-gating process. If the time marker pulses where tagged with a modulation (modulator and 100 mc clock would be phase-locked), the correct time marker could be picked out to an accuracy of one nanosecond. One of course must still know the total delay up to that range-gate interval to one nanosecond. However,

* Analysis similar to the above could be done by photographing each return on a Tektronix 519 scope and by reading the information contained on the negatives into the computer. This would be a very slow process. A storage mode on the 519 would allow about as fast a processing as the first method described.

a modulator, scaler, and preset unit should be available or developed to determine the delay up to the range-gate interval and order the logic to commence range-gating as described above. The modulator and present unit would be triggered on the outgoing laser pulse.

6. Past Experience

a. Photomultiplier tubes

Dr. Robert Detenbeck of our Quantum Electronics group is obtaining detailed information on photomultiplier-tube response to single photoelectrons in his work on photon-counting statistics.

b. Optical Radar Work at the University of Maryland

An optical radar has been developed at the University of Maryland to sound the upper atmosphere. A concise description of the radar is given in the accompanying reprint. The ranging scheme is essentially the same as that presented above except that a 15 MHZ clock is all that is needed and no delay is needed because the range is quite small (and can be read from the ordinal number of range interval on the computer printout).

Using the optical radar developed by McCormick, Poultney, Alley et al,[1] an attempt was made in October 1965 to range to the moon using the 100 joule mode of operation of the laser. The constraint of working in the north-south meridian severely hampered the attempt. The range was predicted from the ephemeris and entered in a Hewlett Packard 5264 A Preset Unit used in conjunction with a 5245 L Counter. At the proper time, the preset triggered an oscilloscope which was used as the vernier. A schematic diagram is given in Figure 1. The limiting factor in range accuracy was probably the rise time of the pulse from the preset unit ($\sim$ 100 nanoseconds). No attempt was made to

1 P. McCormick, S. Poultney, C. Alley, et al, Nature, page 209 (1966)

(Reprinted from Nature, Vol. 209, No. 5025, pp. 798-799, February 19, 1966)

Optical Radar Detection of Backscattering from the Upper Atmosphere (75–160 km)

An optical radar system has recently been used to detect and study backscattering from the upper atmosphere (75–160 km). Although a much more detailed investigation is in progress, our preliminary results seem to indicate rough agreement with those of Fiocco and Smullin[1]. Those authors suggested micrometeorites as a source of the echoes. When observations were made for brief time intervals (0·5 h or less), peaks were sometimes observed in the return-signal profiles. It should be noted, however, that when averaged over a period of several hours the return signal tends to become relatively smooth. It would seem, therefore, that the altitudes of the scattering layers, if they exist, fluctuate rapidly with time. The total scattering cross-section at 6943 Å observed by us is of the same order of magnitude as that reported by Fiocco and Colombo[2] ($\overline{N\sigma} \approx 10^{-11}$ cm^{-1}).

The optical radar consists of a Korad *K*-2*Q* ruby laser which is capable of producing single pulses containing 6–10 J at 6943 Å with a width of 10 nsec and a beam divergence of no more than 10 milliradians. The ruby is 8 in. long, 5/8 in. in diameter and is surrounded by a helical flash lamp. *Q*-spoiling is achieved by means of a Kerr cell. The laser pulse is brought to a focus at a 1/8 in. diameter aperture in a rotating mirror. The aperture is located in the focal plane of the University of Maryland's 20-in. reflector, which is a Broken Cassegrain with a 300-in. effective focal length. The beam divergence of the light leaving the telescope is less than 0·4 milliradians. In order to prevent air breakdown, the rotating mirror is installed in a chamber which is evacuated to a pressure of about 10μ mercury. An average energy of 1·0 J per pulse was sent into the atmosphere. Each laser pulse was monitored for proper firing time and for pulse amplitude. The return signal from the telescope is reflected by the rotating mirror to the cathode of a cooled E.M.I. 9558*B* photomultiplier tube (*S*-20 cathode) which is gated off during the actual laser firing. A 10 Å pass-band interference filter was used in the experiment.

Due to the small magnitude of the signal, the experiment consists of counting individual photoelectrons. The pulses are processed by Chronetics Nanologic Modules and sent through logic circuits[3] to an 'on-line' *CDC* 160 computer which is programmed[3] to store the counts from each altitude interval. At present the system is capable of obtaining an atmospheric scattering profile, for each laser pulse, with an altitude resolution of 2·5 km.

All measurements were made at College Park, Maryland (76° 57′ W. long., 39° N. lat.), while looking at the zenith.

Figs. 1 and 2 give the results for two nights out of five for which we have obtained data. Fig. 1 shows the result of a series of shots taken during a short time interval. The scattering appears to be enhanced over the altitude ranges from 100 to 125 km. The total number of counts received (in 10 pulses) from 75 to 150 km was 2,240. The background was 350 counts. The number of photo-electrons due to backscattering is thus 1,890 with a mean error of 51 due to statistical uncertainty. Fig. 2 [illegible] average of 100 laser pulses, over a period of [illegible], [illegible] different night. The magnitude of the return signal is much lower than in Fig. 1 and no peaks are present. For the range 75–150 km we have: a total return of [illegible] counts, a background of 3,330 counts, a backscattering of 1,740 counts with a mean error of 147 counts. The high background is due to the fact that we use the same optical path for both transmitting and receiving. It is difficult to shield the phototube completely from the high light-levels present and from ruby fluorescence. Background measurements were made, during observations, by placing a black cloth over the end of the telescope tube.

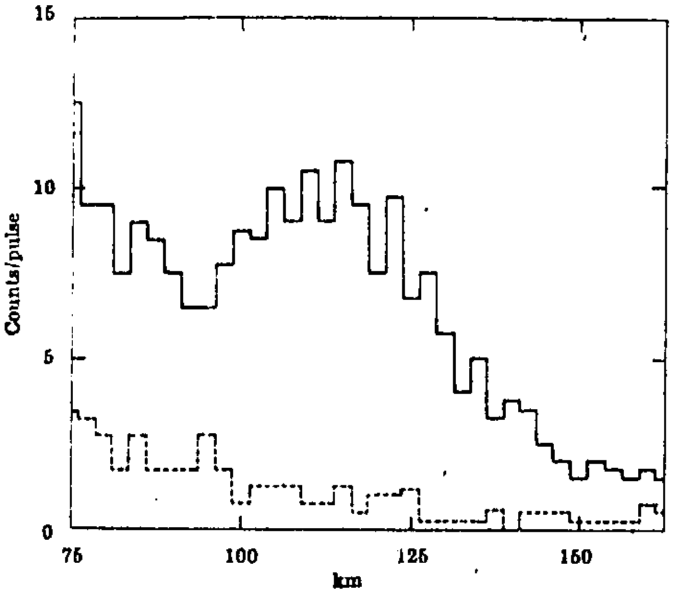

Fig.1. October 29, 1965, 07h 30m—08h 00m U.T. ——, Observed return (average of ten laser pulses); – – – –, background (average of ten laser pulses)

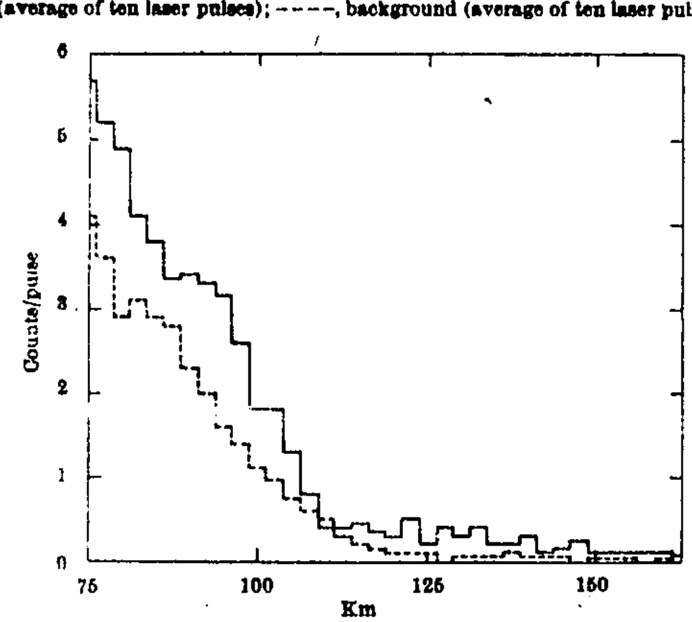

Fig. 2 October 31, 1965, 05h 30m–09h 30m U.T. ——, Observed return (average of one hundred laser pulses); – – – –, background (average of twenty laser pulses). (Note change of vertical scale from that of Fig. 1)

We thank Prof. S. F. Singer for his encouragement and advice. This work was supported, in part, by the U.S. Weather Bureau under grant *WBG–4–FY*–64 Advanced Research Projects Agency contract *SD*–101, National Aeronautics and Space Administration grant *NGR* 21–002–022 and Bureau of Ships contract *NObsr* 72710.

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[1] Fiocco, F., and Smullin, L. D., *Nature*, 199, 1275 (1963).
[2] Fiocco, F., and Colombo, G., *J. Geophys. Res.*, 69, 1795 (1964).
[3] Perschy, J., M. S. Thesis, Univ. Maryland (1965).

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shorten this pulse further. Jitter of the output pulse was reduced by starting on the lamp firing signal. Recall that in conventional operation the laser output consists of a series of microsecond pulses spread over a millosecond. Photographs of each output pulse were taken so that correlation techniques could be used on the returns. Indications made it probable that the ranging was a success, but no conclusive proof could be obtained due to the limitations of not being able to track the moon and the slow firing rate of the laser; only 2 shots per pass being possible. The attempts were postponed indefinitely. At about the same time the noise rates of dark and bright moons were also obtained.

Further experience will soon be gained in timing when another ranging experiment is completed. This experiment will test the hypothesis that the penetration distance of a light pulse in a cloud is related to cloud thickness. The exact shape of the return pulse as well as the range will be measured. A circuit similar to Figure 1 will be used except an EGG Gate Generator will be the master control and will gate an EGG Discriminator used in place of the Discriminator-Coincidence Circuit combination (see Figure 2). The pulse shape will be read off oscilloscope 1 (Tektronix 519) photographically and the range from oscilloscope 2 (Tektronix 564).

The timing circuits eventually used for the moon-ranging experiment will probably closely follow a combination of Figure 2 and the logic and data-processing scheme of Poultney, McCormick, Alley et al.[1]

See the discussion above and Figure 3.

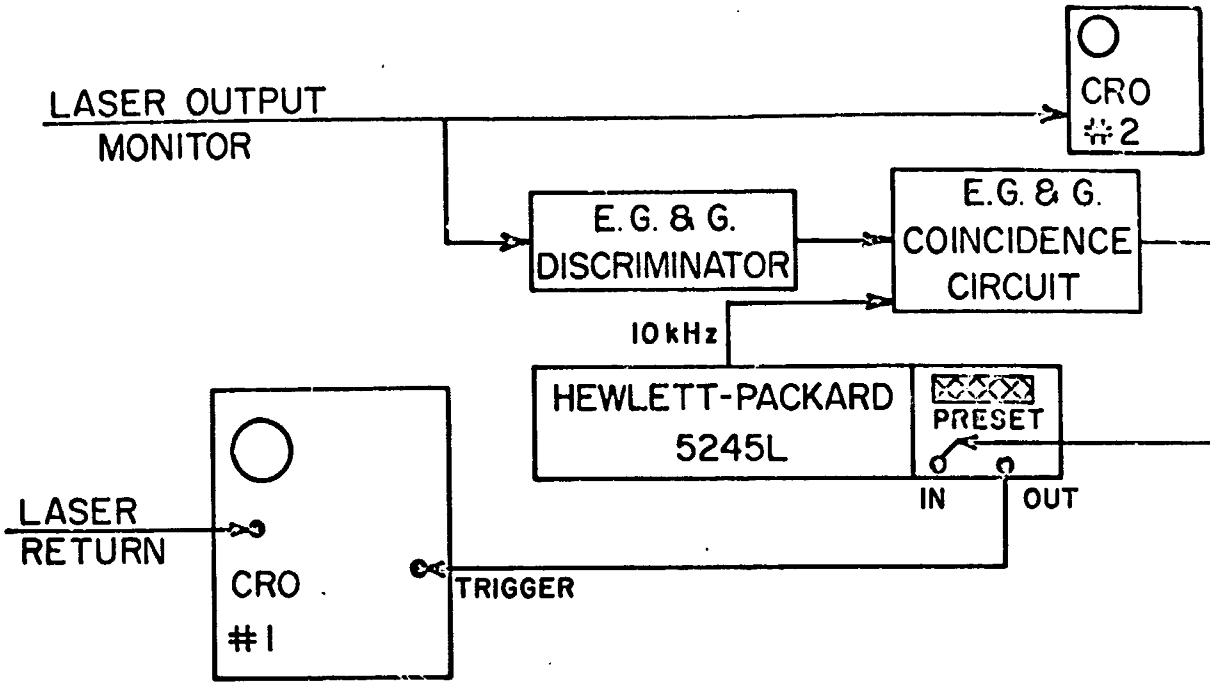


FIG. 1 MOON-RANGING CIRCUITS (OCT. 1965)

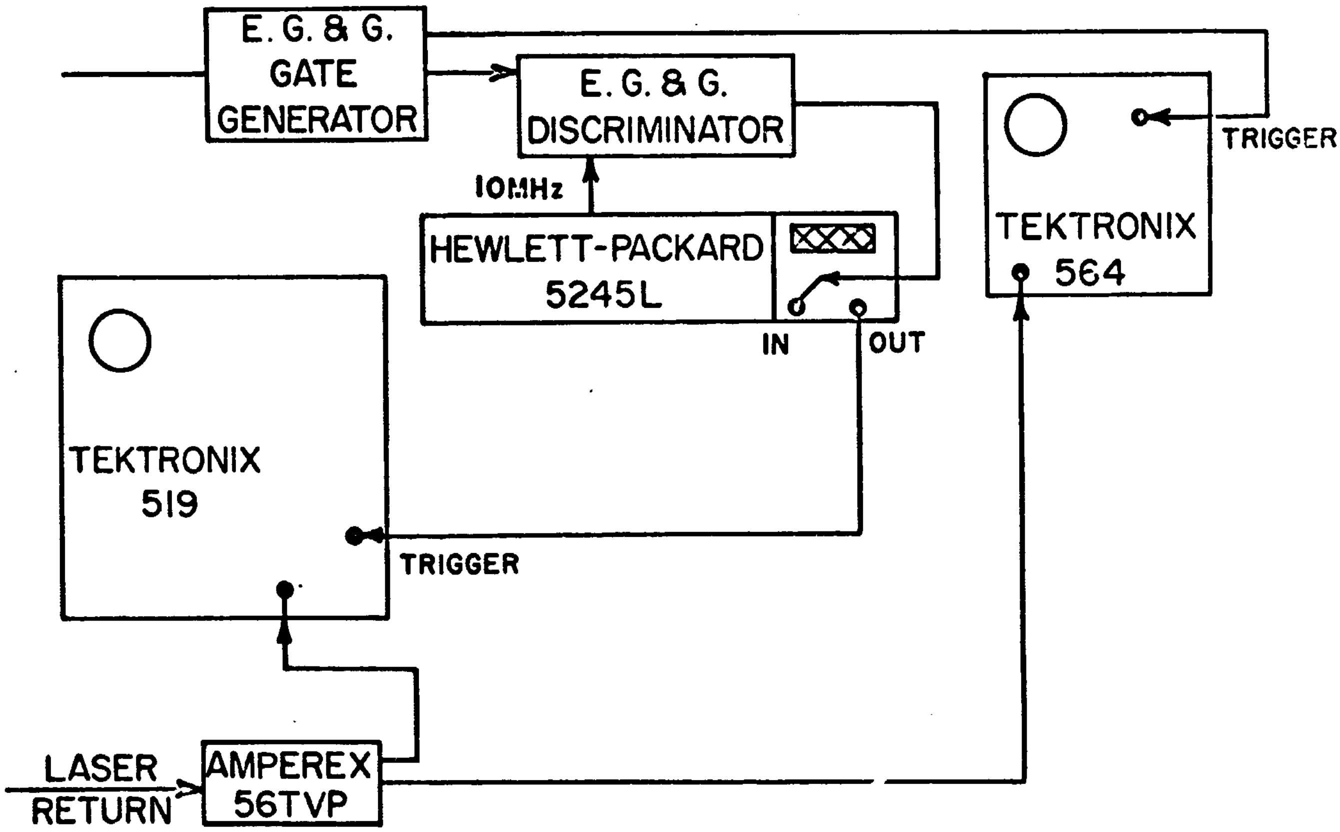


FIG. 2 CLOUD PENETRATION EXPERIMENT

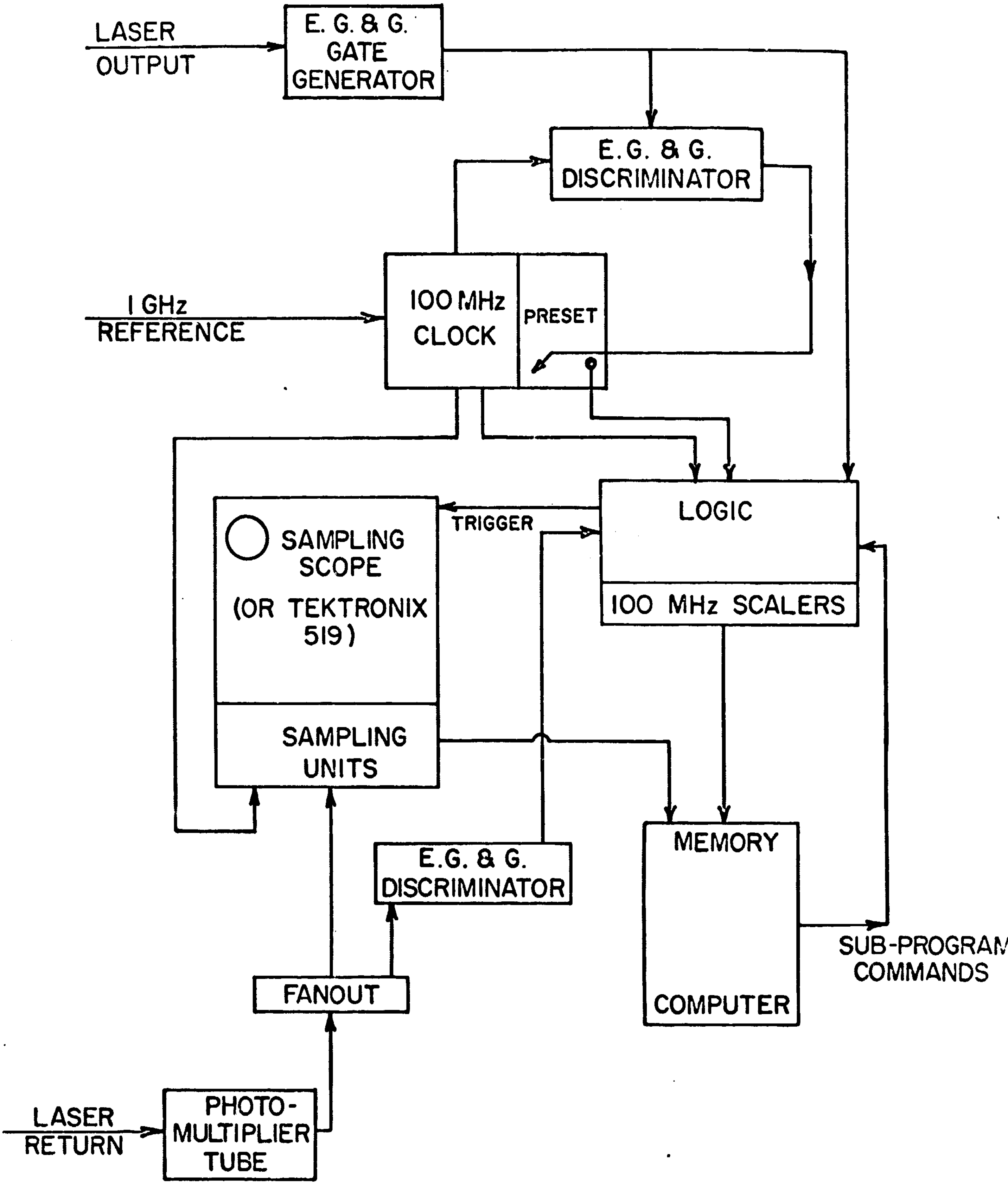


FIG. 3 PROPOSED LUNAR RANGING CIRCUITS

TABLE I

Certainty of Location of Retroreflector as a Function of Noise Rates, Signal Magnitude, Number of Firings, Discriminator Dead Times, and Range Gate.

A. $\Phi = 13 \mu rad$, $R_B = 2 \times 10^7$ photons/sec, $\tau_o = 10$ nsec, Disc. at single-photoelectron level (1).

N's / m	1.6 (1)	3.2 (2)	4.8 (3)	6.4 (4)	9.0 (5)
1	46	2650	>>	>>	>>
2	63	5000	>>	>>	>>
5	120	18,000	>>	>>	>>
10	220	61,000	>>	>>	>>
20	440	>>	>>	>>	>>
40	880	>>	>>	>>	>>

B. $\Phi = 130 \mu rad$, $R_B = 2 \times 10^9$ photon/sec, $\tau_o = 10$ sec, Disc at single p.c. level (1) [Here neither setting discriminator at two photo-electrons or a large number of firings helps very much.]

Nεs / m	(1) 1.6	(2) 3.2	(3) (4.8)	(4) 6.4	(5) 9.0	(10) 16
1	0.92	1.05	1.21	1.40	1.60	1.80
2	0.92	1.05	1.21	1.40	1.60	1.80
5	0.92	1.05	1.21	1.40	1.60	1.80
10	0.92	1.05	1.21	1.40	1.60	1.80
20	0.92	1.05	1.21	1.40	1.60	1.80

c. $\Phi = 40 \mu rad$, $R_B = 2 \times 10^8$ photon/sec, $\tau_o = 10$ nsec, Disc at single p.e. level.

Nεs / m	(1)	(2)	(3)	(4)	(5)	(10)
1	4.4	25	137	760	>>	>>
2	4.4	25	137	760	>>	>>
5	4.7	26	145	800	>>	>>
10	5.3	34	200	1300	>>	>>
20	7.0	63	550	>>	>>	>>
40	11.0	165	2300	>>	>>	>>

Explanation of Table I

1. Parameters

ϵ = Quantum Efficiency of Photomultipliers = 0.10

s = return signal (all within 10 nanosecond) = 16 photons

R_B = noise rate of bright moon (and blue sky)

= 2×10^7 photons/sec for a single 60" telescope with Φ = 13 μradians and 10 Å filter

R_D = noise rate of dark moon (+ receiver scatter)

= 2×10^4 photons/sec for same telescope.

T = initial range gate = 1000 nanoseconds (1/3 km)

m = range gate intervals = 1, 2, 5, 10, 20, 40

N = number of firings = 1, 2, 3, 4, 5, 10

2. Calculations

It is assumed that the noise is Poisson-distributed in time and that the detection statistics is Poisson-distributed in amplitude.

a. With the discriminator level set at the single photoelectron level, the probability of recording the signal (in its bin with no noise) is 0.80 on one firing (and on N firings).

b. The probability of recording noise in a resolution time, τ_o, is $P_o = (1.00 - e^{-\epsilon R \tau_o})$. τ_o will usually be 10 nanoseconds although it may be chosen larger. In this case, the proability of recording a bright moon background count is 0.02. Φ = 13 μrad.

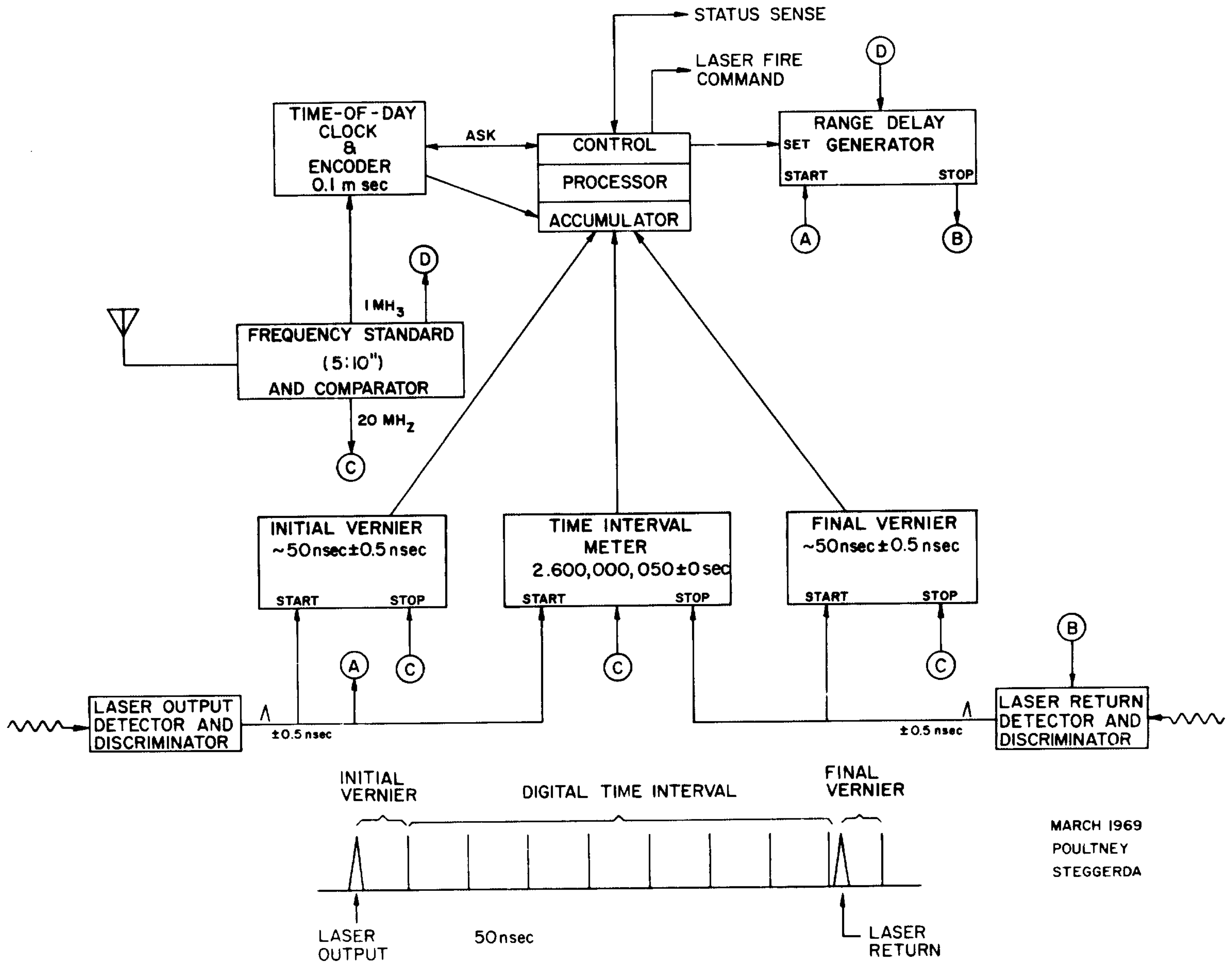
c. The probability of one noise count in the internal $(^T/m)_j$ is taken to be $P_1 = P_o(1 - e^{-\epsilon R T/m})$ as long as T/m 10 nanoseconds. The probability of recording b noise counts in internal $(^T/m)_j$ is P_1^b.

d. A measure of the certainty that the reflecto has been located in a certain interval $(^T/m)_j$ after N shots is found by dividing the probability of recording the expected signal ($N\epsilon s$) in that interval by the probability of finding $b = N\epsilon s$ in the same interval. Tables of this measure of certainty appear above.

APPENDIX I.

Concept of Maryland Lunar Ranging Electronics (March 1969)

CONCEPT OF MARYLAND LUNAR RANGING ELECTRONICS



MARCH 1969
POULTNEY
STEGGERDA

APPENDIX II.

Details of Lunar Ranging System Van (March 11, 1969)

UNIVERSITY OF MARYLAND
COLLEGE PARK, MARYLAND
20742

COLLEGE OF ARTS AND SCIENCES
DEPARTMENT OF PHYSICS AND ASTRONOMY

March 11, 1968

Mr. Walter Carrion
Code 524
Goddard Space Flight Center
Greenbelt, Maryland 20771

Dear Walt:

Here follow the details on the Lunar Ranging System Van.

1. General Environmental Requirements

a. The temperature inside the van shall be regulated to $\pm$ 2°F no matter what the external environment. Ambient can be about 23[illegible].

b. Incandescent lighting should be used in the amount sufficient for the work area.

c. Particular care shall be taken with foreseeing and eliminating ground loop, rfi, and power surge problems.

2. Equipment List

The list of equipment to be installed in the van appears as Appendix I. Most of the equipment fits in 19" racks and s[illegible] the height of the front panel is given. Also given are the power requirements for each item. GSFC will supply similar numbers for the laser and its accessories.

3. Equipment Layout

The majority of items listed in Appendix I are tied together as shown in Appendix II, Ground Station Lunar Ranging System. Not shown on the circuit diagram is the test equipment listed in Appendix III. Provision should be made in the van for storing this test equipment as well as for a work bench area with a tool storage board on the wall above it and shelves or drawers for spare parts below. Space for six twelve volt batteries and charger should be available near the time-keeping rack.

Two console areas should be provided. One for the laser operator and one for the computer-ranging operator. It is natural to place the laser console and equipment at a closed end o[illegible] the van where it may be screened-off if necessary. A preferred layout is shown in Appendix IV for the van floor plan. Appendix V is a rack layout for the ranging system.

4. Van Power Needs

There should probably be three separate power mains. One for the lighting and environment control in the van, one for the laser equipment including the water cooling equipment external to the van, and one for the Ranging System. Totaling the power requirements of Appendix I yields 4500 watts with a safety factor of 50% for the Ranging System.

5. Communication and Warning Provision

Provision shall be made for a two-way communication system between van and 60" dome. Stations are needed in the van at each console and three stations are necessary in the 60" dome.

Provision must also be made for a warning light and warning buzzer in the 60" dome which is controlled from the laser console.

6. Ranging System Cable Connections to Dome

Cable connections to the dome consist of:

a. Eight signal cables (RG 8U)

b. Three high voltage cables (> 3 KV)

c. Two d.c. power lines (6, 12 v)

7. A shielded loop antenna must be mounted on top of or at the side of the van.

Yours truly,

Sherman K. Poultney
Assistant Professor of Physics

SKP:MM

Enclosures

Appendices I, II, III, IV, V

APPENDIX I:

EQUIPMENT FOR LUNAR RANGING SYSTEM

1. Time Interval Meter — Eldorado 783G

   5 1/4" high 17" deep 19" rack

   25 lbs.

   1.5 amps 115 V 60 Hz 1 phase

2. Time Delay Generator — Eldorado 650

   5 1/4" high 17 1/2" deep 19" rack

   30 lbs.

   2 amps 115 V 60 Hz 1 phase

3. Time Code Generator — Astrodata 7190

   3 1/2" high 20" deep 19" rack

   30 lbs

   1/2 amp 115 V 48-400 Hz

4. Analog to Digital Converters in DATUM Mounting Chassis — #2101-201

   7" high 10 1/2" deep 19" panel

   Requires 4 slots in rack (25 available)

   Requires + 5V at 300 ma + 15 V - 15 V at 60 ma

5. Computer System (except Teletype)

   Cabinet 22" wide, 83" high, 27" deep, 200 lbs., 115 V, 7.5 a

   a) Computer — VArian 620 i

      10 1/2" high 22" deep 19" rack

      67 lbs.

      3 amps 115 V 60 Hz

   b) Tape Recorder — Digidata #1300

      12 1/4" high 16" deep 19" rack

      38 lbs

      1.5 amps 115 V 60 Hz

   c) Memory Expansion Chassis — Varian Option

      10 1/2" high

      Optional Power supply 3 amps 115 V 60 Hz

6. Teletype — ASR-33

Systems rest on floor

≈ 40 lbs.

3 amps 115 V 60 Hz

7. ECG and Ortec System — 401A/402A (2 each)

2 bins required with Power Supplies

6 plugs in modules/bin

≈ 8 3/4" high 19" rack

115 V, 100 watts each

2 Units Ortec 437 TPHC

3 Units Ortec 417 Disc.

2 Units Ortec 425 Delay

2 Units EGG C104 Coincidence with Veto

2 Units Ortec 403 A Time Pick-Off

8. Delay Box — DB263 EGG

3 1/2" high 7" deep 19" rack

no power

5 lbs. 9 oz.

9. WWV Receiver — Beckman 905

5 1/4" high 14" deep, 20 lb.

115 V, 125 watts

10. Keithley 246 High Voltage Supplies (3 each)

5 1/4" high 10" deep, 25 lbs.

110 V, 105 watts

11. Quartz Oscillator with X4 Multiplier (20 MHz) — Sulser 2.5C

5 1/4" high, 11 3/4" deep, 19 lbs.

115 V, 25 watts

12. Tracor VLF Tracking Receiver and Frequency Calibrator (with Loop Antenna) — 599J

7" high, 16 1/2" deep, 50 lbs.

115 V, 25 watts

13. <u>0.1 Millisecond Time Interval Meter
HP 5245M with HP 5262A Plug-In</u>

5 1/4" high, 16 3/8" deep, 32 lbs.

115 V, 95 watts

14. <u>Filter Temperature Control and Monitor
(with built in Chart Recorder</u>

8" high, 10" deep, 20 lbs.

115 V, 30 watts

APPENDIX III

RANGING ELECTRONICS TEST EQUIPMENT

1. Pulse Generator — HP8004A

   6 1/2" high, 11" deep, 7 lb.

   115 V, 30 watts

2. Fast, Portable Oscilloscope — Tek 454

   7 " high, 17 3/4" deep, 33 1/2 lbs.

   115 V, 125 watts

3. Multi-Channel Analyzer — Northern Scientific 601 (256 channel)

   12" high, 22" deep, 40 lbs.

   115 V, 75 watts.

   (must plug-in when necessary to ASR-33 or chart recorder)

4. Sampling Oscilloscope — Tek 564

   7" high, 18 7/16" deep, 33 3/4 lbs.

   115 V, 240 watts

   (contains 3576 and 3T77A plug-ins)
   (Option for 3A6 and 3B3 plug-ins)

5. PEK LIght Pulser (115TR) with Huggins 961D Pulse Generator

   Storage 1' x 1' x 2", 30 lbs.

   Used on work bench

   115 V, 25 watts

6. Cerenkov Light Source Box w/Dark PMT Test

   No power
   Storage 3' x 3' x 2'
   Used on work bench

7. Ortec Counting Equipment
   401A/402A Module Bin and Power Supply

   8.7" high, 16" deep, 35 lbs.

   115 V, 100 watts

   (contains Ortec 420, 435, 425, 408, 411, and 437)

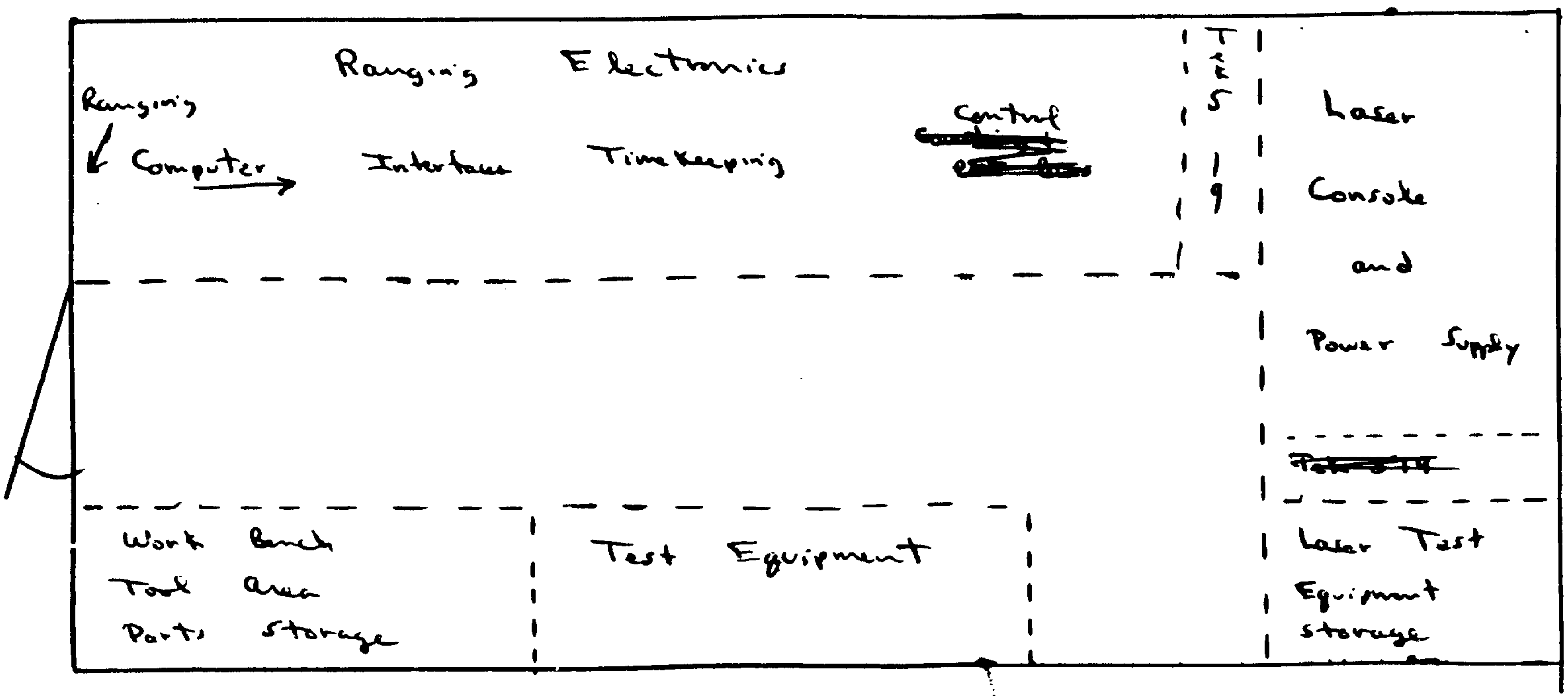
8. Bausch and Lomb Monochromator — Storage

9. Eppley Thermopile — Storage

Stf & Munk

Van Layout – Maryland Suggest

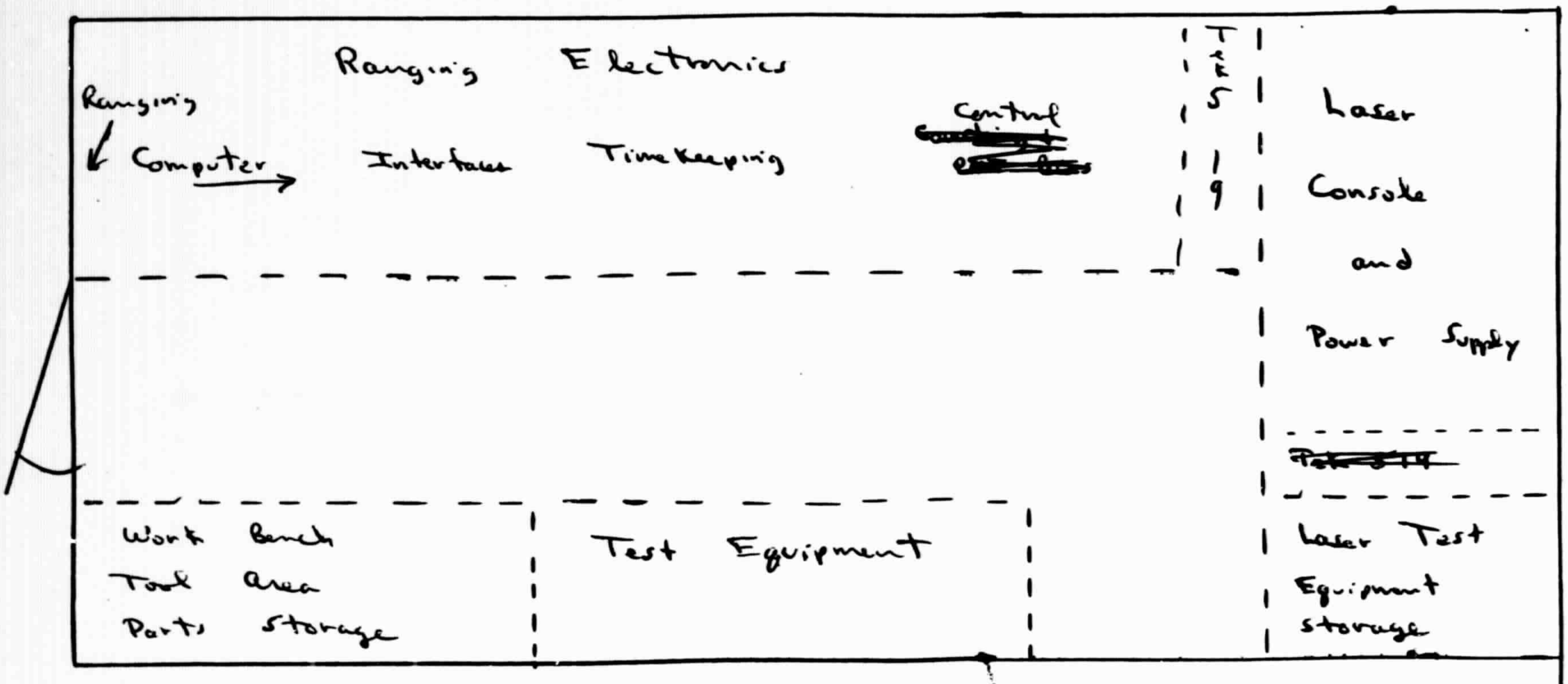
APPENDIX IV



Stf 8 Munich

Van Layout - Maryland Suggest

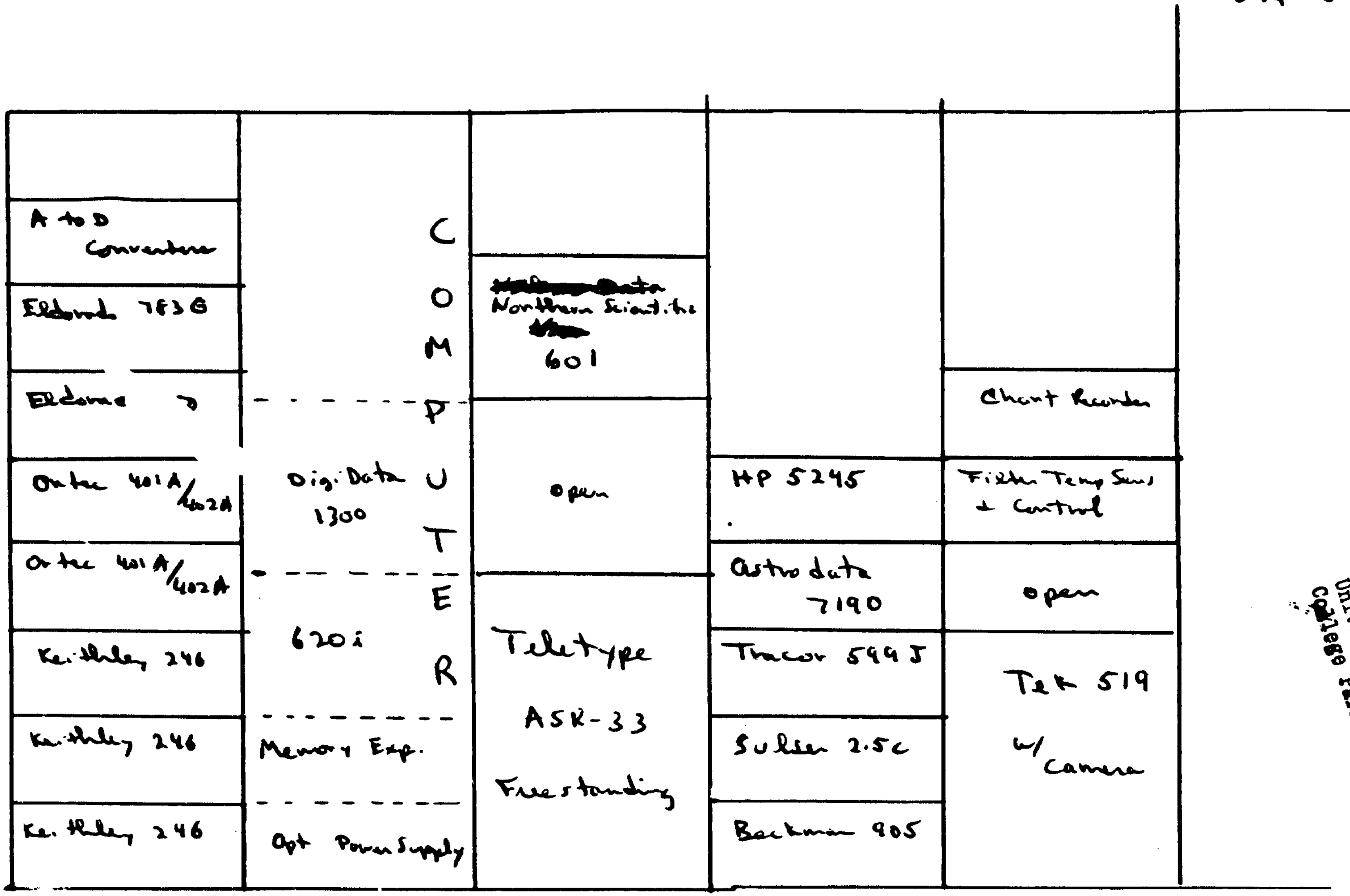
APPENDIX IV



Appendix V

RANGING ELECTRONICS RACK LAYOUT

SKP 8 March



LASER

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Appendix V — RANGING ELECTRONICS RACK LAYOUT

SKP 8 March

LASER

Dr. Sherman K. Poultney
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University of Maryland
College Park, Maryland 20742

Ranging	Computer		Time Keeping	Control
A to D Converter	C			
Eldorado 783G	O	Northern Scientific 601		
Eldorado	M P			Chart Recorder
Ortec 401A/402A	Digi Data 1300 U	open	HP 5245	Filter Temp Sens & Control
Ortec 401A/402A	T E		Astrodata 7190	open
Keithley 246	620i R	Teletype ASR-33 Freestanding	Tracor 599J	Tek 519 w/ Camera
Keithley 246	Memory Exp.		Sulzer 2.5c	
Keithley 246	Opt Power Supply		Beckman 905	