Settling on the moon

Four-beam radar system that guided Surveyor 3 to the moon will also furnish the velocity and range data to land the Apollo lunar module

By Charles J. Badewitz

Ryan Aeronautical Co., San Diego, Calif.

A landing radar that proved its capability by guiding Surveyor 3 to its landing on the moon last month also will provide the data needed to land the first manned Apollo lunar module (LM) on the surface of the moon.

As the two-man LM descends toward the moon's surface at about 60 miles per hour, its landing radar will be switched on at an altitude of 50,000 feet. About three minutes later and 10,000 feet nearer, the radar will begin to make continuous range measurements, and at 25,000 feet it will begin computing the velocity of the module. The range and velocity data will be processed along with auxiliary data from other sensors and the results fed to the landing control system to insure a soft and safe landing. Once the spacecraft lands, the radar's work is completed and it remains on the surface of the moon as part of the lunar module's descent stage.

The landing radar uses a three-beam doppler velocity sensor and a single-beam alitmeter to measure the spacecraft's velocity and range relative to the lunar surface.

The radar return signal in each of the velocity sensor's receiver beams is mixed with a portion of the transmitted signal. The output of the mixers are audio doppler frequencies that are proportional to the spacecraft's velocity components along the respective beams. Frequency data converters break down the doppler frequencies into velocity components in vertical, lateral, and longitudinal antenna directions and relate them to the spacecraft's coordinate system.

The radar altimeter's return signal is also mixed with a portion of the altimeter's transmitted pulse. This produces a frequency proportional to the spacecraft's height above the moon plus a frequency corresponding to the vehicle velocity along the altimeter beam. The latter is removed in the range data converters by utilizing the doppler signals in velocity beams 1 and 2.

After processing by the radar, the velocity and range data is sent to the lunar module's guidance computer in a serial binary form, and as pulse trains and d-c analog voltages to the astronauts' visual displays.

The landing radar's data will be combined with altitude and velocity signals from the space vehicle's inertial measuring unit. These data inputs are weighted by the spacecraft's height above the moon's surface, and programed to assure the guidance computer receives the most accurate input. Errors in the inertial system tend to increase with time. Landing radar errors, on the other hand, are determined primarily by velocity and altitude, therefore they decrease as the velocity and altitude decreases.

The initial effect of the radar data on the spacecraft's guidance system is small, and increases as the descent progresses. However, as the data from the landing radar is factored into the guidance computer, it reduces the effects of accumulated errors in the inertial unit; thus the landing radar updates the inertial measuring unit.

Integrated Antenna

The four radar beams are generated by two planar arrays on the single integrated antenna assembly pictured on page 113. The groups of alternate slotted waveguides in the large center section

The author

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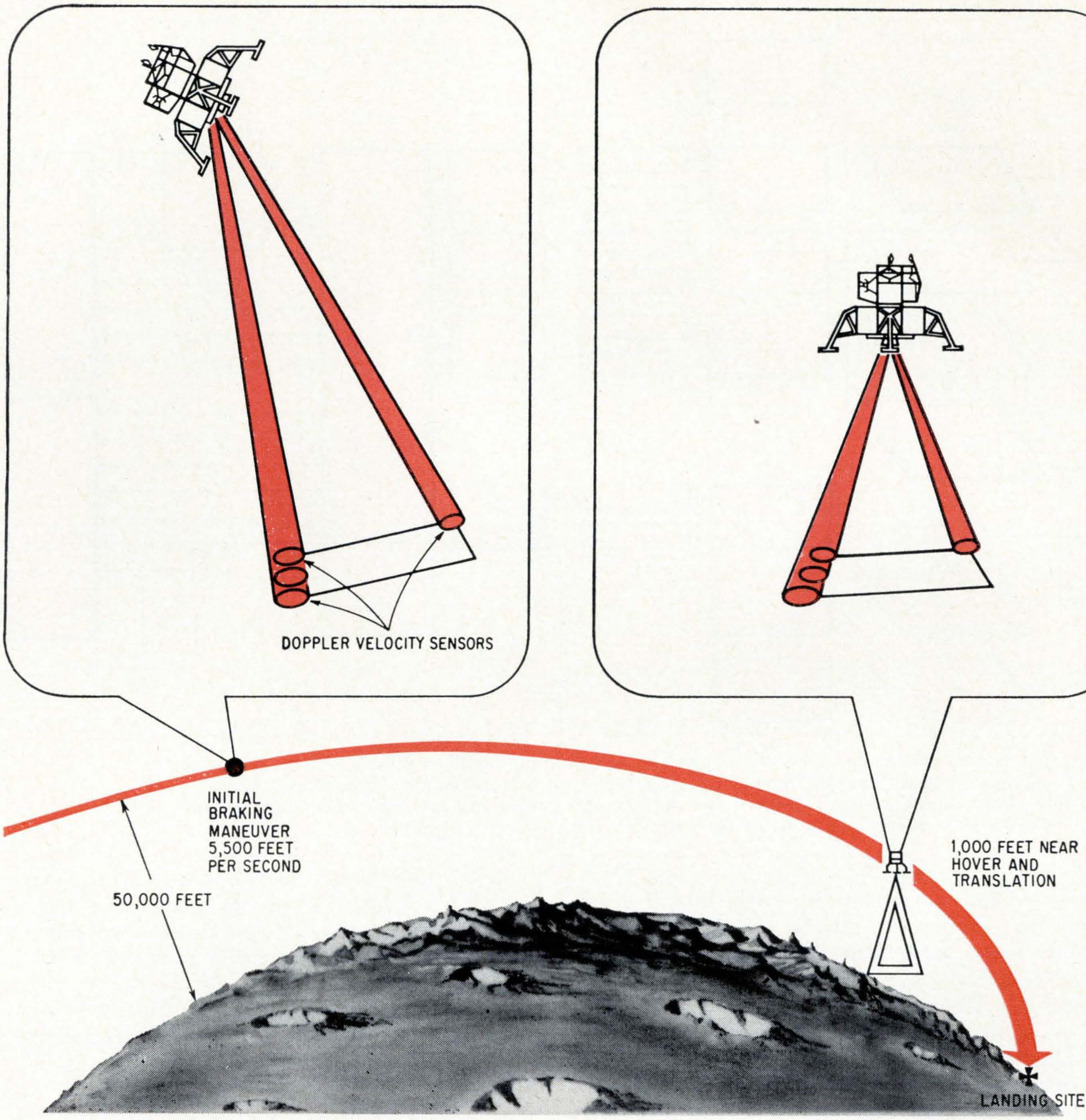


Powered descent begins when lunar module's altitude is about 50,000 feet. Throughout the tilt maneuver, the four radar beams are kept pointing at the lunar surface automatically by the guidance computer. The repositioning is accomplished by rotating the antenna of the landing radar around the Y axis into either of two positions.

are the transmitting antennas; the receiver antennas are the outrigger sections around it. The E-plane slotted guides in the center section transmit the altimeter frequency-modulated continuous wave; and the alternate H-plane slots transmit a c-w velocity sensing signal.

The three narrow beams from the velocity sensor antenna emanate from the planar array in the same manner as legs are extended to form a tripod.

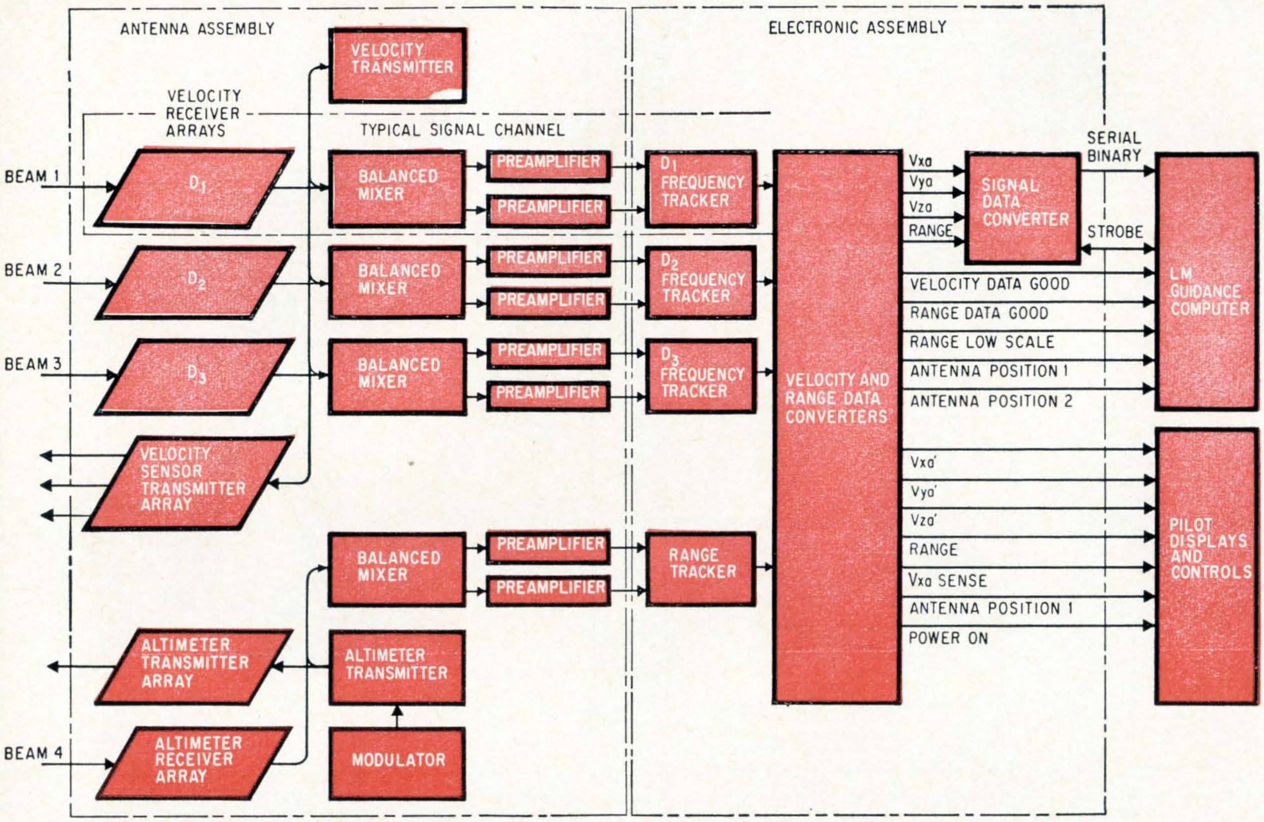
The attitudes of the beams during the initial braking and hover maneuvers are illustrated by the drawing shown above. The multiple beams are generated at fixed angles relative to a line drawn perpendicular to the face of the planar array. The outrigger receiving arrays, which have the same slot orientation as the velocity transmitter array, are the three broadside arrays. Their geometries make each receiving beam axis colinear with the corresponding transmitted beam axis.

The altimeter's receiving array is boresighted so that coincidence of its main lobe with the altimeter transmitter's main lobe is achieved, yielding in turn the desired two-way pattern for the altimeter.

Perpendicular beams

The antenna is mounted on a rotating pedestal on the underside of the spacecraft's descent stage. The antenna can be rotated about the spacecraft's Y axis, into either of two positions, automatically by the guidance computer, or manually by the pilot as the craft's attitude changes. This keeps the radar beams as nearly perpendicular to the lunar surface as possible.

The diagram on page 114 details the basic op-



Lunar module's landing radar combines transmitter velocity and altimeter signals with the signals in return beams to produce doppler frequencies proportional to the spacecraft's velocity and range from the moon. Data converters break down the doppler signals into velocity components in the X, Y, and Z direction. These are input signals for the module's guidance computer.

eration of the radar's velocity sensors. The beam angles and the energy pattern shown are for beam 1, but the patterns and angles for the other two velocity beams are similar.

Two orthogonal sets of velocity components are measured in the coordinate system of the antenna. The V_{xa}, V_{ya}, and V_{za} components are shown on page 114, where V_{xa} coincides with the center line of three velocity sensor beams and V_{ya} lies in the plane of velocity sensor beams 1 and 2. The coordinate system for V_{xa}', V_{ya}' and V_{za}' velocity components is rotated about the V_{ya} axis through an angle, ζ, to cause V_{xa}' to lie in the plane of beams 1 and 2. The primed velocity components are used only for the pilot's visual displays.

To determine velocity, the radar return signal is mixed with a portion of the transmitted signal. This is a process of direct radio-frequency to audio-frequency conversion which produces doppler frequencies proportional to the component of the spacecraft's velocity along the beam of concern. These frequencies, D_1, D_2, and D_3, are combined to produce the orthogonal velocity components such as V_{xa}, V_{ya}, and V_{za}.

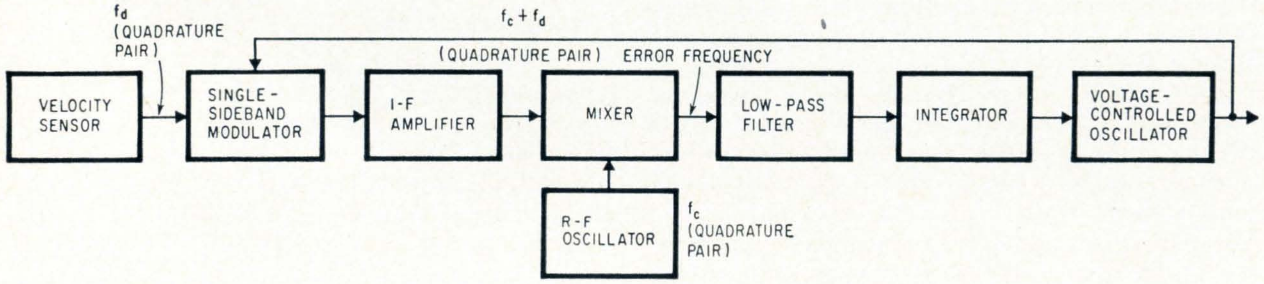
For example, the component of velocity relative to the antenna axis, V_{xa}, is computed as follows:

$$V_{xa} = -\frac{\lambda}{2\cos\Lambda\cos\xi}\,\frac{(D_1 + D_3)}{2} \qquad (1)$$

Where:

λ = electromagnetic radiation wavelength
Λ = beam 1 antenna angle
ξ = beam 3 antenna angle
D_1 = doppler shift along beam 1
D_3 = doppler shift along beam 3

The following equation computes the range to the lunar surface. The $K(D_1 + D_2)$ term is the cor-



LM's frequency tracker is a closed loop servosystem that processes sensor and reference signals.

rection factor which compensates for doppler shift in the range beam.

$$R = \frac{c}{2S} [f_a - K (D_1 + D_2)] \quad (2)$$

where

R = range to the lunar surface
c = speed of light
S = altimeter's transmitter frequency deviation rate
f_a = altimeter's received frequency, including range and doppler components
K = scaling constant
D_2 = doppler shift along beam 2

The radar antenna assembly divides each doppler signal in quadrature pairs. The beam's quadrature outputs are amplified and used as input signals to the frequency trackers in the electronic assembly. Then recombination of the quadrature pairs and single sideband comparison techniques in the frequency trackers validate the signals and measure magnitude and sense of velocity.

The radar's receiver uses narrow-band filter circuits (labeled frequency trackers in the block diagram) to detect doppler signals, and to separate the true doppler signal from noise background.

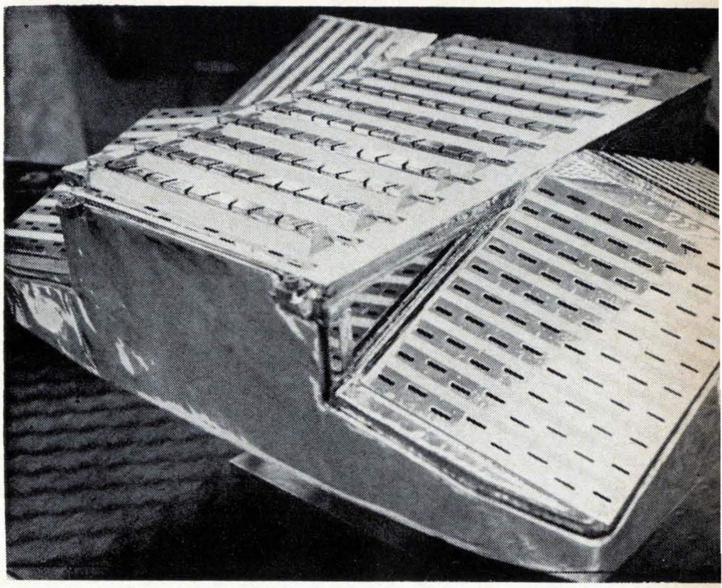
The operation of the frequency trackers is traced by the block diagram below, left. The tracker is basically a closed loop servosystem whose inputs are the doppler quadrature pair, f_d, from the radar velocity sensor, and another pair called the carrier quadrature pair, f_c, from a fixed r-f oscillator.

The input circuit of the frequency tracker is a single sideband modulator which accepts the doppler quadrature pair input and another feedback quadrature pair, approximately equal to $f_c + f_d$, from a voltage-controlled oscillator. The single sideband modulator output is amplified by an intermediate-frequency amplifier and mixed with the f_c quadrature pair in a second mixer.

The output of that mixer is the error frequency of the tracking loop. This signal is filtered, integrated, and used to drive the voltage-controlled oscillator. The oscillator's output is applied to the frequency converters and also fed back and used as a carrier frequency for the single-sideband modulator. Under tracking conditions, the output of the single sideband modulator is very nearly the same as the carrier frequency f_c.

Once the true doppler signal is acquired, it is tracked with a high order of accuracy, about 0.1%, and the tracker output frequency is almost the same as the center frequency in the received doppler signal band.

Each beam's frequency tracker sends a doppler signal to the velocity and range data converters along with a d-c step voltage that indicates acquisition and authentication of a true lunar return signal. The converters then translate the doppler signals into orthogonal velocity sets in the coordinate system of the antenna. The guidance computer uses this data to steer the lunar module. Equation



Landing radar antenna is covered with special thermal finish to protect it against extreme temperatures in space. The center section contains the altimeter and velocity sensor transmitting antennas. The outrigger antennas at either side of the center section are for the receivers.

Radar system characteristics

Type of system	
velocity sensor	c-w, 3-beam
radar altimeter	f-m/c-w
Altitude capability	
velocity	5 to 25,000 feet
altimeter	10 to 40,000 feet
Velocity capability	V_{xa} −2,000 to +500/fps.
	V_{ya} −500 to +500/fps.
	V_{za} −500 to +3,000/fps.
Altimeter antenna	
type	planar array
gain	50.4 db
beamwidth	3.9° E plane
	7.5° H plane
Velocity sensor antenna	
type	planar array
gain	49.2 db
beamwidth	3.7° E plane
	7.3° H plane
Transmitters	
type	solid state
frequency	
velocity sensor	10.51 Ghz
radar altimeter	9.58 Ghz
Output power	
velocity sensor	200 mw min. (50 mw per beam)
altimeter	175 mw min.
Altimeter	
modulation	sawtooth f-m
frequency	130 hz
deviations	208 Mhz and 42 Mhz
Response time	
25,000 feet	0.1 sec

Why did Surveyor 3 bounce?

When Surveyor 3 hopped and skipped on the moon last month, many people were concerned that the same thing could happen to the Apollo lunar module when it reaches the moon's surface. If it does happen, it probably won't be the fault of the landing radar. Apollo will use an updated version of the radar system aboard Surveyor 3. The landing radar will only indicate the range to the lunar surface during the last seconds of flight; the actual landing will be made by the astronauts.

What really happened to Surveyor 3? The scientists at the Jet Propulsion Laboratory at Pasadena, who control the Surveyor program haven't made known the results of their investigation into the cause—but one can speculate.

During a normal Surveyor descent, the spacecraft slows to about five feet per second at 100 miles altitude. At this point, the craft becomes practically weightless because the moon's gravitational pull is 1/6 the force of the earth's, and the Surveyor's retrorockets are thrusting in the opposite direction to the pull. All the while, the spaceship's guidance computer is receiving velocity and range signals from the landing radar. As the craft passes the 14 foot mark, the radar generates a range mark which the Surveyor's control system uses to cut off the engine. Surveyor then falls free the remaining distance to the moon.

A landing with the engines still burning is actually a softer landing than normal — because of the weightlessness. But the spacecraft would come down, touch, bounce, and touch again, and continue to do so until the ship's momentum is dissipated in the bounces.

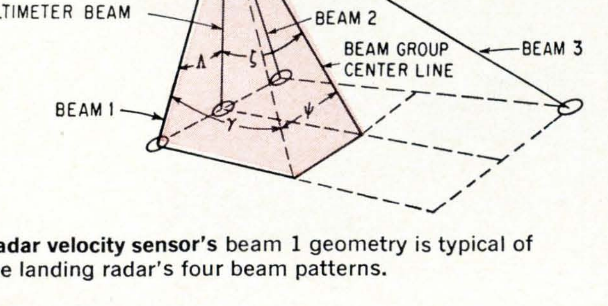
Ryan Aeronautical Co. engineers tend to disclaim early theories that the radar caused the engine cutoff failure by sending confusing signals to the guidance computer. If one of the three velocity sensing beams were pointed down to a hole, it may have generated some contradictory data concerning the Surveyor's velocity across the lunar surface. However, the engine cutoff is made by a signal generated by a fourth beam—the altimeter—and if this beam was pointing down a hole the spaceship would have thought it had farther to go.

Once before at the test station at Holloman Air Force Base, New Mexico, the Surveyor's engines didn't cut off and it bounced. No damage was done to the spacecraft or any of the instruments on board. That time the scientists said it was the fault of the spaceship's instrumentation, not the radar. In the case of Surveyor 3, Ryan engineers think the same thing may have happened.

W.J.E.

1 shows how the sum of the doppler signals from beam 1 and beam 3 are multiplied by a constant coefficient (which is a function of the beam angles) to yield V_{xa}. V_{ya} and V_{za} and the range are obtained in a similar manner.

The measurement of range is accomplished in an analogous manner, the only difference being that some compensation for the doppler shift along the range beam is required. This is provided in the velocity and range data converters by summing the doppler frequencies in beams 1 and 2, scaling the summation, and subtracting the result from the doppler frequency in the altimeter return signal.



Radar velocity sensor's beam 1 geometry is typical of the landing radar's four beam patterns.

The measured range and the velocities are held ready in the radar's signal data converters for readout when requested by the guidance computer. The computer samples the velocity and range data sequentially in a cycle that repeats every 80 milliseconds.

Spurious signal rejection

The basic task of the frequency trackers is to detect relative motion between the vehicle and the lunar surface. However certain physical objects on the lunar module, such as hold-down belts that come loose when the LM and the command and service module separate, may be in the radar beam and moving—thus causing spurious signals. To avoid acquisition and tracking of these signals, unique circuitry has been incorporated into frequency trackers to examine all signals during the search mode and reject all except the true doppler return signal.

The logic used in rejecting spurious signals is based upon recognizing that returns from the vibrating physical elements contain double sidebands. True doppler signals have just one sideband. The technique that is used to discriminate against spurious signals is simply one of examining the signal level in the positions of both sidebands. The tracking filter examines the level in one sideband; and a noise-sampling filter examines the level in the other. A comparison is made and if the signal-to-noise ratio exceeds a prescribed value, the acquisition circuitry allows the frequency tracker to track the signal.

Digital tester okays Apollo's altimeter

Specially designed test set counts frequency and averages it over the pulse period to measure slope and linearity accurately

By V.M. Andreone and J.H. Poirier

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Before it leaves the earth, the radar that will guide the Apollo lunar module to a safe touchdown on the moon's surface will be checked out with equipment that has no precedent or peer.

Like most of the electronic hardware aboard the lunar module, the radar altimeter has some extraordinary test requirements. In almost every subassembly, the Ryan Aeronautical Co. engineers encountered test problems that could not be solved with existing equipment.

For example, the frequency modulator, the heart of the radar altimeter that makes continuous measurements of the spacecraft's distance from the lunar surface, required gear with a measurement accuracy 10 times better than the tightest modulator tolerance. And the equipment must determine inaccuracy in an altimeter that will operate at 25 times the height (50,000 feet) and twice the frequency (X band, 5.2 to 10.9 Ghz) of conventional airborne pulse radar altimeters.

Since no commercial test equipment could meet specifications, Ryan engineers developed their own digital test set. Made with off-the-shelf integrated circuits, it samples the modulator's radio-frequency output and counts the changes in the output frequency as a function of time. By averaging the frequency changes, the r-f wave's sweep rate or slope is determined as well as the r-f pulse's linearity and upsweep and downsweep times.

The digital averaging measurement technique can also be used to plot any periodic frequency-modulated signal as a function of time, provided that the pulse time period is greater than the test equipment's 700-microsecond sampling time.

Glossary of terms

Downsweep average slope, m:

The frequency deviation over the downsweep period divided by the downsweep period, T.

$$m = \frac{1}{T}\int_0^T \frac{df\,(t)\,dt}{dt} = \left(f_H - f_L\right)\frac{1}{T}$$

where f_H and f_L are the high and low limits of the modulated transmitted frequency.

Linearity, l:

The percentage deviation from the downsweep average slope, m, of the measured average slope for any 10% portion of the total downsweep period.

$$l = \left[\left(\frac{df}{dt}\right)^* - m\right]\frac{100}{m}$$

*average value over 10% segment of T

Downsweep/Upsweep ratio, a:

The ratio of the downsweep time period to the upsweep time period.

$$a = \frac{T}{t'}$$

Sweep cycle, t_s:

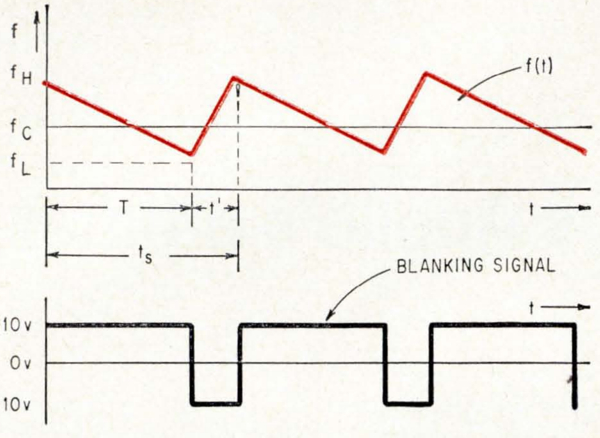
The time required to complete one downsweep and one upsweep cycle.

$$t_s = T + t'$$

Altimeter operation

The output frequency of the radar altimeter's modulator varies as a sawtooth function, shown on page 116, from a center frequency of 99.79 megahertz. Frequency multipliers raise the output to an X-band center frequency, which is transmitted to the lunar landing surface. The radar return signal is received, amplified, and the doppler frequency component extracted.

A portion of the downsweep section of the transmitted and return signal is sampled by the



Frequency of Apollo radar altimeter's modulator varies as a sawtooth function with a center frequency of 99.79 Mhz. A blanking pulse synchronized to the r-f wave is also produced. Frequencies f_H and f_L are the upper and lower band limits of the sawtooth; and T and t' are the downsweep and upsweep pulse periods.

altimeter's range processing circuitry, and the instantaneous frequency difference, Δf, between the two is determined. This frequency difference is related to the range between the spacecraft and the moon's surface by the equation

$$\Delta f = (f_T - f_R) = m\left(\frac{2R}{c}\right) \pm f_d \qquad (1)$$

Where

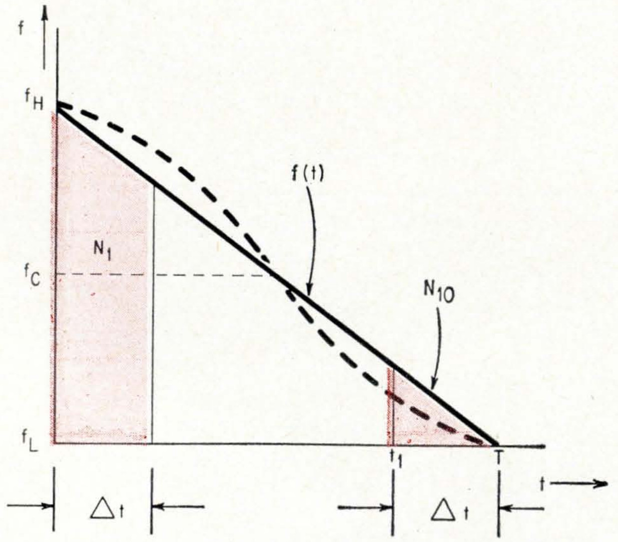
f_T = transmitted frequency
f_R = received frequency
R = range
f_d = doppler frequency
m = average sweep rate = rate of change of the transmitted frequency as a function of time
c = velocity of light.

The range is proportional to the difference in frequency between f_T and f_R and inversely proportional to m, the average sweep rate or slope. As equation 1 reveals, small variations in sweep rate have a large effect on range measurement. Specifically, a 1% error in average slope is reflected as a 2% error in range.

The altimeter's frequency modulator operates in three modes. In mode 1, there is a high deviation frequency. It is used when the spacecraft descends from an altitude of 2,500 feet to the lunar surface. In this mode, the output frequency varies from 99.998 Mhz to 99.582 Mhz, a deviation of ±208 khz.

A large frequency deviation is required for a more accurate range determination. The second mode is switched in when the spacecraft is at an altitude above 2,500 feet. In this mode, the frequency only deviates 41.6 khz. In both modes 1 and 2 the output waveforms are the same with equal sweep times. The third mode is called the deviation-inhibit mode. As the name implies, the output frequency is a constant, unmodulated 99.79 Mhz. Mode 3 is actually a built-in test mode for center frequency checks and is not utilized during flight.

In addition to the r-f output, the modulator also generates a blanking signal. This signal has the same time period as the downsweep portion of the r-f pulse; and is synchronized with the sweep function. The blanking signal is present only during operation in modes 1 and 2.



Frequency modulator's average slope is represented by the solid line between f_H and f_L. Nonlinearities are depicted by the dashed inverted S-curve. The tinted areas are equivalent to the change in transmitter frequency during pulse sample intervals N_1 and N_{10}.

Tight test tolerances

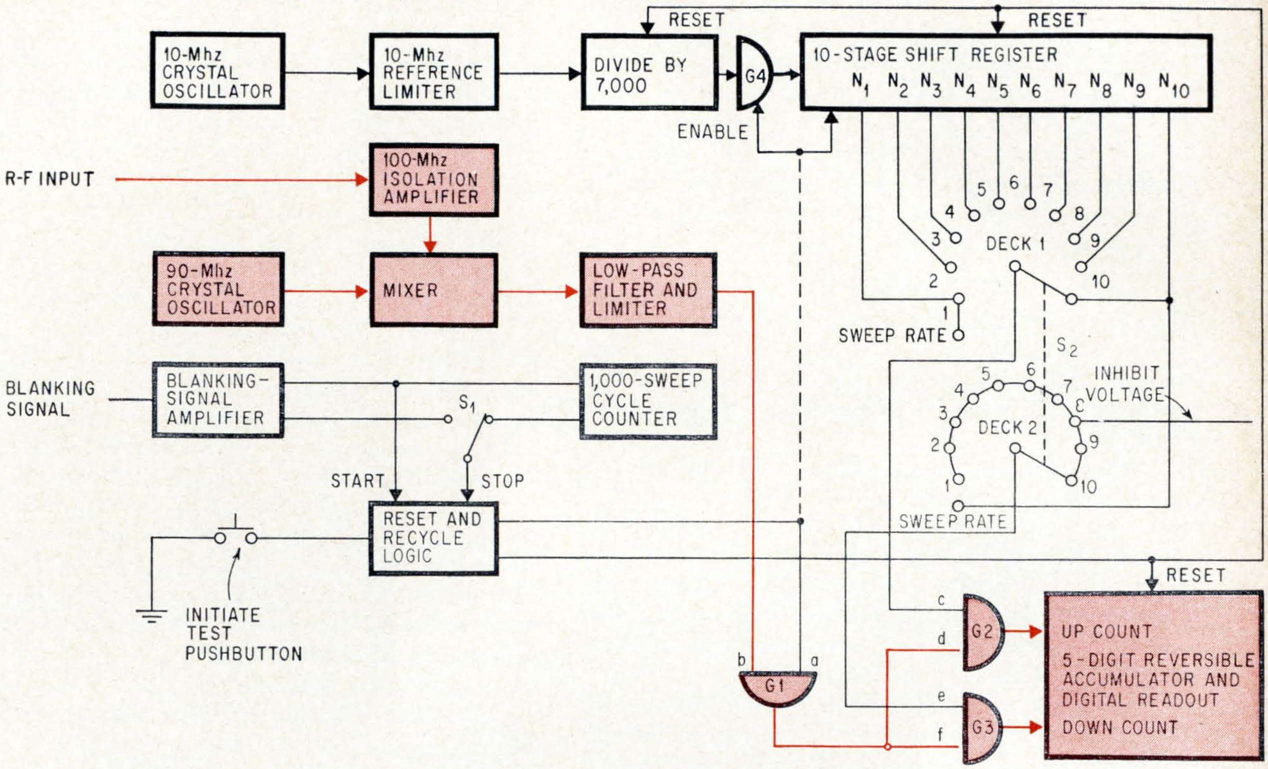
The downsweep average slope proved to be the most difficult modulator parameter to test. It must be measured within an accuracy of 0.05%, 10 times better than the slope tolerance itself. In the low deviation mode, the digital test set had to detect a change of 500 parts-per-million in a slope of approximately 12 megahertz per second. This is equivalent to a change in slope of 6,000 hertz per second. Therefore, over one sweep cycle, the maximum allowable frequency deviation is 42 hz.

Since linearity measurements are qualitively the same as the sweep slope measurement, the 5% linearity specification is easily implemented by whatever technique is chosen to detect changes in slope. Measuring center frequency within 0.05% accuracy is not a major problem since the absolute value of the center frequency is very large.

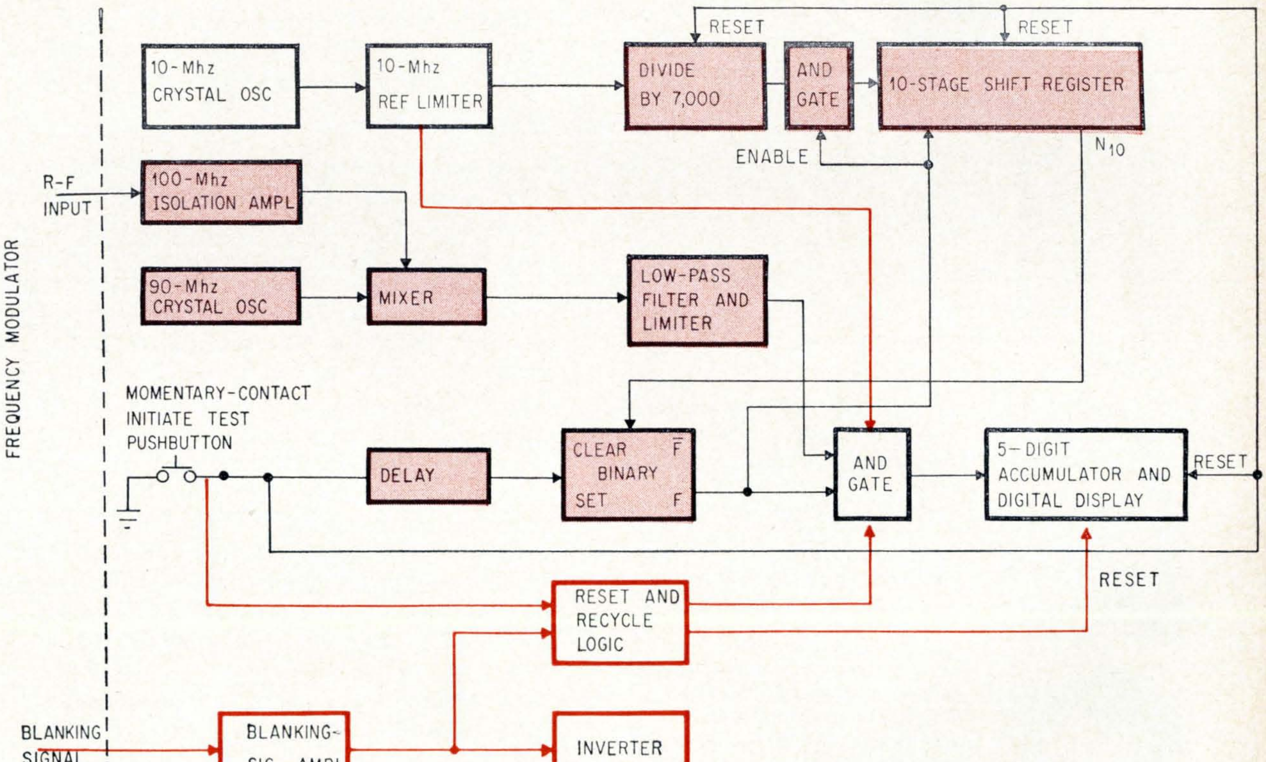
The test set measures the sweep slope by directly sampling the frequency modulators r-f output. The digital averaging technique is unaffected by center frequency fluctuations and more than meets the test's accuracy requirements. Linearity and center frequency error measurements result naturally from the slope measurement.

The quantity $\Delta N = N_1 - N_{10}$ is independent of center frequency. The larger the sampling intervals, the larger the value of ΔN for a given value of m; thus, the resolution improves as the sampling interval increases.

However, there is a tradeoff to be considered. As the sampling interval increases, the slope average is taken over a progressively smaller portion



After mixing and filtering, modulator's r-f output passes through AND gates into the digital test set's count accumulator. Sweep rate (average slope) measurements are made by putting S_2 in the sweep rate position and averaging the transmitter frequency over one cycle. This determines the most significant digits. Averaging the frequency over 1,000 cycles determines the least significant digits.



Center frequency measurements are made by the test set's configuration, shown in tint. One microsecond after the test button is pressed, the binary circuit enables the AND gate and the accumulator counts r-f pulses until the end of the shift register's time interval, N_{10}. This count is proportional to the center frequency. To measure upsweep and downsweep time, the test set is switched to the configuration represented by the blocks outlined in solid color. The black-bordered blocks are used during both tests.

of the downsweep cycle. Furthermore, the longer the sampling interval, the greater the effect of nonlinearities on the measurement of average slope.

Linearity measurement

The worst-case nonlinearity in the frequency modulator output is ±5%. For a given nonlinearity, L, the percentage error, p, in the calculated slope for a given $T/\Delta t$ ratio is:

$$p = L/[T/\Delta t] - 1$$

For these tests, a value of 10 was selected for $T/\Delta t$ based upon the maximum allowable slope error in the modulator's output, the time allowed for averaging, and cost consideration in implementing the balance.

Digital averaging techniques are accurate if a sufficient number of sweep samples is used.

An error analysis by a Ryan Aeronautical Co. mathematician, Robert Golden, determined that averaging the results of four consecutive sets of 4,500 sweep-rate measurements, each in the low deviation mode, and each set having an inherent accuracy of 0.5%, yields a new accuracy of 0.025%. By averaging an error over a greater number of sweeps, accuracies within 0.01% can be achieved.

The test set also measures the modulator's center frequency drift to an accuracy of 0.0012%.

Pulse counters

The top diagram on page 117 demonstrates the mechanization of the sweep rate and linearity measurement system. The clock is a 10 Mhz oscillator whose output is divided to form a train of pulses, each 700 microseconds in length. The 700-μsec pulse period is the desired sampling interval. The pulse train is a source of shift pulses for a 10-stage shift register wired so that only one stage can contain a logical 1 at any time. A shift pulse advances that 1 from one stage to the next. As a result, lines N_1 through N_{10} will each carry a pulse consecutively, for a period of 700 μsec. With the downsweep portion of the blanking signal initiating this shifting sequence, the net result is to divide the downsweep period into 10 subperiods of 700 μsec.

The r-f input from the modulator is buffered by passing it through an isolation amplifier, and mixed with the output of a 90-Mhz crystal oscillator. The difference frequency is filtered and limited and made available for counting at intervals corresponding to the selected value of Δ N.

By means of switch S_1, the frequency over 1 or 1,000 sweep cycles can be averaged. A test over one sweep cycle determines the most significant digits of the measurement. A second run over 1,000 cycles defines the least significant digits.

The two-deck rotary switch S_2 performs the logic that enables the test set to distinguish between nonlinearity and sweep rate tests.

To measure sweep rate, switch S_2 is placed in the SWEEP RATE position. In this position, the signal on the wiper of the first deck is N_1. Also N_{10} is connected through the wiper on the second deck to input e of gate G_3. This permits the processed r-f signal to pass through to the accumulator during these intervals, for 1- or 1,000-sweep cycles, depending on the setting of S_1.

During the N_1 time interval, the r-f input drives the reversible accumulator in a positive direction; during the N_{10} interval, the accumulator is driven in the opposite direction . The result is Δ N, which is accumulated for 1 or 1,000 sweeps, and read out on the digital display.

When the rotary switch is in positions 1 through 9, the gate G_3 at the DOWN input of the accumulator is inhibited, and a measure of the frequency within the selected interval is obtained. The UP input is enabled during this interval, and as before, either 1 or 1,000 consecutive readings may be stored, and read out at the end of the test.

Finding f_c

In the lower diagram on page 117, the tinted sections show how the test system is configured to make mode 3 center frequency measurements. During this test, the blanking pulses are not used.

To make the test, the operator presses the initiate test pushbutton. This resets the divide-by -7,000 timing circuit, the 10-stage shift register, and the 5-digit accumulator, and after a 1-μsec delay, sets the binary logic circuit which enables the timing generator and the AND gate input to the accumulator. Processed r-f pulses from the mixer are passed by the AND gate into the accumulator. The trailing edge of the N_{10} interval pulse, which occurs 7,000 μsec after the start of delay, clears the binary and terminates the frequency count. The accumulator's digital readout then shows a count which is proportional to the modulator's center frequency.

The blocks outlined in solid color illustrate the test system's configuration when checking sweep times. For this test, the r-f input is removed and the blanking signal used. The clock signal is gated by the upsweep or downsweep portions of the blanking signal into the accumulator for one cycle. The resulting count of the clock frequency is proportional to the up- or downsweep period.

The authors

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