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THE ROCKET-GRENADE EXPERIMENT

by W. Nordberg and W. Smith

Goddard Space Flight Center
Greenbelt, Maryland

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SUMMARY

This manual describes the grenade technique which is employed to measure average ambient temperature and winds in horizontal layers between two successive grenade explosions. The technique is effective up to altitudes of ninety km. The method for deriving pressures and densities from the temperature information is discussed in detail. And finally, rocket-borne and ground-based instrumentation is delineated.

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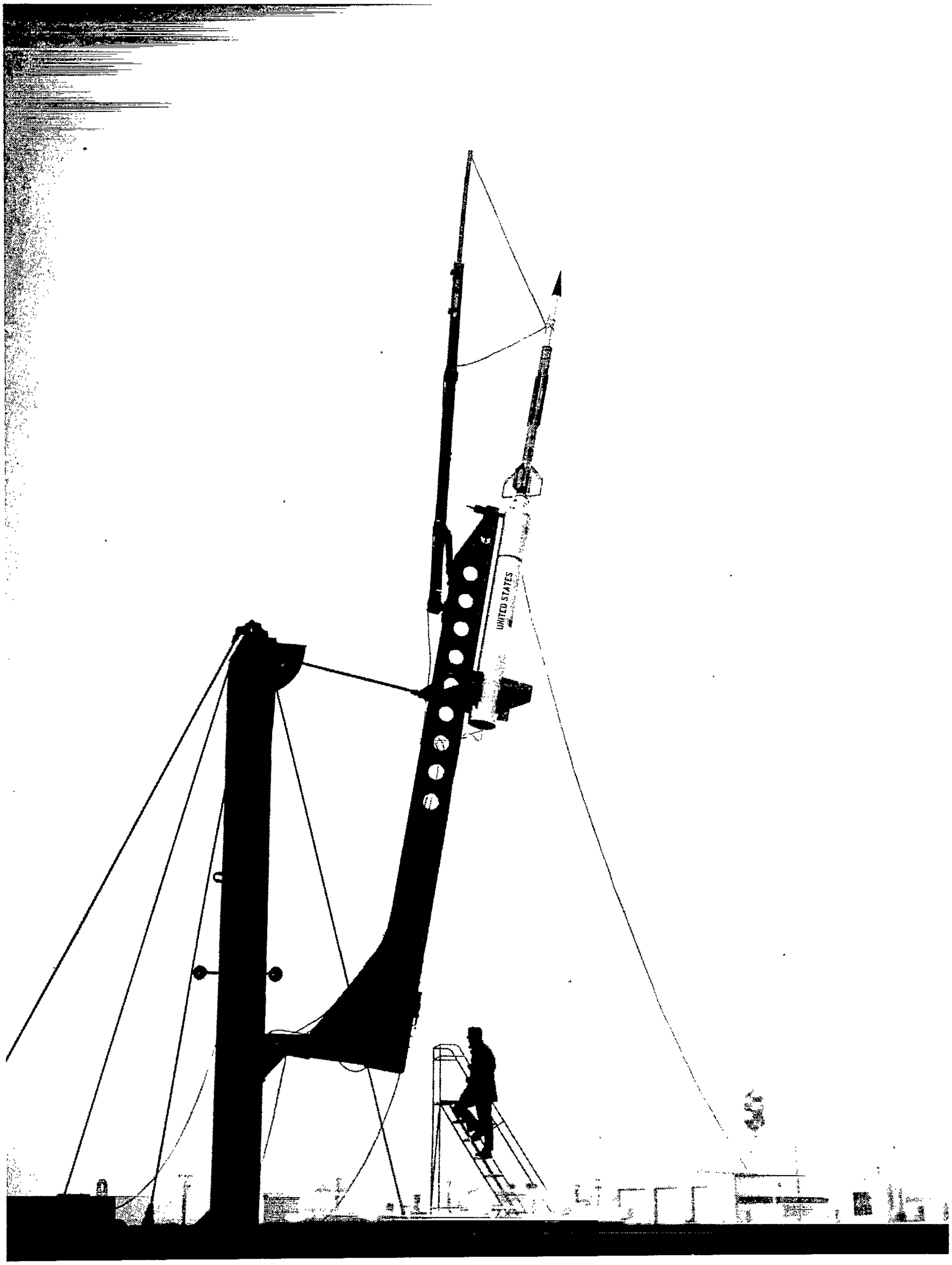

Rocket-grenade experiment

THE ROCKET-GRENADE EXPERIMENT

(Manuscript received July 15, 1963)

by
W. Nordberg and W. Smith
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INTRODUCTION

The operation and performance of the rocket-grenade experiment is presented and intended to serve as a reference manual, reviewing the experiment techniques for the benefit of persons wishing to apply this experiment to their own needs. The purpose of the rocket-grenade experiment is to measure wind velocities and temperatures, and to derive densities and pressures, by detonating explosive charges (grenades) at predetermined height intervals during the ascent of the rocket to altitudes of approximately 90 km. The sound energy from the explosions is recorded by a microphone array on the ground. The time and direction of the arriving sound wave are calculated. The rocket position is accurately determined by a combination of radar, DOVAP (*Do*ppler *V*elocity *A*nd *P*osition), and optical-tracking systems. An analysis of these coordinates yields the direction and magnitude of the sound-velocity vector in the layer between two explosions; this vector is a measure of the temperature and wind in the layer.

The variations of atmospheric pressure, temperature, density, wind, and composition (humidity) with time and space are conventionally considered the parameters of greatest interest to the meteorologist, because they are presently best suited to describe the processes responsible for various weather conditions. In the past, meteorologists believed that knowledge of atmospheric conditions up to the altitude of the tropopause would be sufficient to describe and predict weather on the earth. However, as measurements at higher altitudes became available, researchers realized that many meteorological phenomena (especially those arising from the interaction between solar energy and the atmosphere) can be understood only by further exploration of the upper atmosphere.

Before World War II, scientists used kits and balloons to extend their knowledge of the atmosphere to higher altitudes. Balloon-borne radio-transmitting meteorological instruments (radiosondes) were introduced in the 1930's, and much valuable information still is accumulated by this method; however, these measurements are limited to altitudes below 30 km. After World War II, the German V-2 rockets were used to extend meteorological experimentation to higher altitudes. Present knowledge of the atmosphere between 30 and 100 km is derived almost entirely from rocket experiments; these experiments have shown that significant dynamic processes and meteorological variability in atmospheric conditions exist up to heights of 80 km.

During and just before the International Geophysical Year (IGY), rocket-grenade experiments were conducted to establish temperature and wind measurements in three typical areas of the globe, selected as best representing atmospheric behavior in the 30 to 90-km region. These three areas were White Sands, New Mexico, in the continental subtropical region; Fort Churchill, Canada, in the sub-Arctic; and Guam, Mariana Islands, in the Pacific equatorial region. A series of 12 Aerobee rockets was successfully fired at White Sands from 1950 to 1953, using ballistic cameras to provide the required tracking data. Ten Aerobee sounding rockets, which measured temperatures and winds up to 95 km, were fired at Fort Churchill, Canada, during November 1956; July, August, and December 1957; and January 1958. The windy, cloudy weather conditions of the Arctic required conversion of this experiment to an all-weather experiment by use of electronic tracking techniques (DOVAP) and of methods to reduce wind noise in the sound-ranging (Reference 1). With these changes, the only weather limitations were those imposed by the rocket ballistics. The results clearly indicated a seasonal and latitudinal temperature variation, with temperatures increasing toward the winter pole at 80 km and toward the summer pole at 50 km. Remarkable temperature inversions between 50 and 80 km with secondary peaks above 50 km were measured in all winter firings at Fort Churchill. In summer, prevailing winds were from the east, usually less than 50 m/sec; in winter, these winds were from the west, usually between 50 and 100 m/sec, but in many instances exceeding 100 m/sec.

Nine successful flights at Guam in November 1958 yielded new data in the near-equatorial region; these flights employed smaller, less expensive solid-propellant rocket vehicles. Since then, a smaller and more efficient payload was developed and flown with Nike-Cajun rockets from Wallops Island, Va. During 1960-61, about ten such flights were successfully conducted with this "post-IGY" instrumentation.

INSTRUMENTATION

The rocket-grenade experiment system performs four essential tasks: (1) Places the payload in the desired trajectory; (2) Produces explosions at desired points along this trajectory; (3) Detects the arrival of the sound energy on the ground; (4) Determines the position and time of each explosion. The description of the instrumentation needed to accomplish each of these tasks is divided into two sections, the first devoted to rocketborne instrumentation and the second to ground-based. All pre-launch control (support) equipment, such as power switching, grenade-ejection timer checkout, and monitoring circuits, is contained in a blockhouse located near the rocket launcher to provide protection for personnel and equipment.

Rocketborne Instrumentation

The rocket presently used for the grenade experiment is the Nike-Cajun (Figure 1). This two-stage combination of solid-fuel rockets is easy to handle and can be launched from a modified transportable Nike launcher. When fired from a near-vertical position, the rocket is capable of carrying the present grenade-experiment payload to an altitude of 69 statute miles (105 km) above sea level. Present payload weight is 60 pounds; however, the drag created by the DOVAP antenna configuration is a greater factor in altitude determination than payload weight. In addition to the normal payload, a 90-pound lead weight was added to the Nike booster to increase stability and reduce lift forces at Nike burnout by reducing Nike burnout velocity; this additional weight, located in the Nike transition section, does not appreciably affect the peak altitude of the experiment because this section is discarded with the empty Nike booster. Additional Nike-Cajun characteristics are given in Table 1. Recovery of the rocket is not required because all results are recorded by ground instrumentation.

Figure 2 indicates the desired rocket trajectory. To produce nearly vertical sound propagation, the explosions should occur in the region above the microphones; this is sometimes difficult to achieve, as safety considerations related to booster and unignited or normal second-stage impact will require some intentional deviation from the optimum trajectory. For maximum accuracy in data reduction, it is also desirable that the rocket's trajectory give all grenades a nearly common line-of-sight when seen from the sound ranging site. In addition, the rocket's trajectory is affected by the wind it traverses, this effect being greatest at lower altitudes where the rocket's velocity is lowest (Table 2). Wind trajectory disturbances are determined and compensated for as follows:

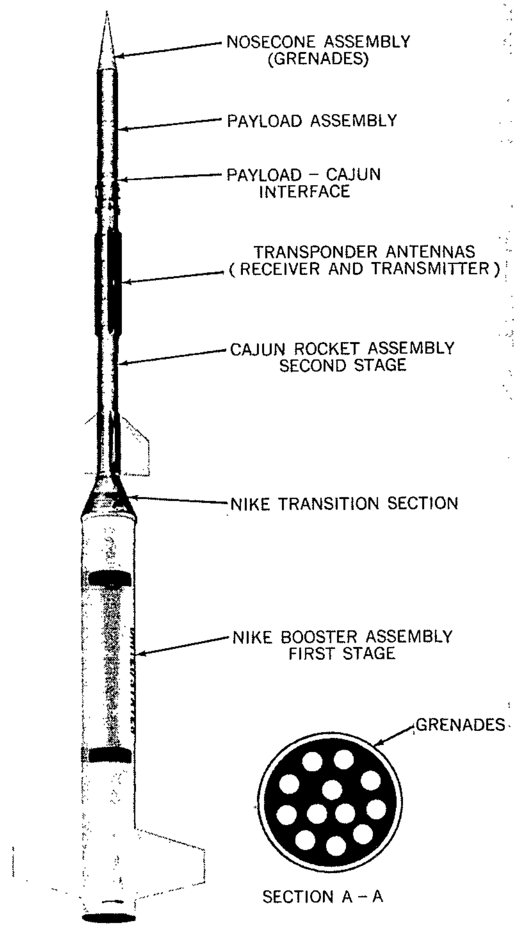


Figure 1—Relation of payload to rocket vehicle.

1. Winds at low altitudes are measured at regular time intervals up to a short time before launching.

2. Winds at higher altitudes are measured a few hours before firing by means of standard radiosonde balloons.

3. The effect of the wind on the rocket is calculated, with the aid of analog or digital computers, by multiplying the measured wind speeds by a unit ballistic wind effect and wind-weighting factors which decrease with altitude. This computation yields a displacement of the impact point due to wind. It is applied to a computed "no-wind" impact point obtained from a launcher-tilt factor relating, generally in a linear fashion, to the launcher elevation angle and the horizontal range of the impact point. Unit wind effect, launcher-tilt factor, and a table of wind-weighting factors are usually predetermined by theoretical calculations and empirical adjustments. These factors are often stored in a computer, which facilitates the determination of launching settings; however, this determination can also be made by manual computations (References 2, 3, and 4).

Table 1

Grenade Experiment—Nike-Cajun Rocket Information

Dimensions (inches)		Performance (60-lb payload)		Weights and Aerodynamic Characteristics	
Nosecone 18° inclination angle	18.8	Booster burnout velocity	3,050 ft/sec	Total Nike-Cajun launch weight	1,550 lbs
Total payload length	56.0	Booster ignition time	0.0 sec	Payload weight	60 lbs
Cajun length	107.0	Booster burnout time	3.5 sec	Payload center of gravity (CG) from nose tip	36.5 in
Second-stage length	163.0	Cajun ignition time	17.0 sec	Cajun burnout weight (with 60-lb payload)	147 lbs
First-stage length	151.0	Cajun ignition altitude	32,000 ft	Burnout CG (from nose tip)	92.5 in
Total length	314.0	Cajun burnout time	19.8 sec	Burnout Mach number (Cajun)	M = 5
Payload diameter	6.75	Cajun burnout velocity	5,400 ft/sec	Burnout center of pressure (Cajun)	$C_p = 105.5$
Cajun body diameter	6.5	Cajun burnout altitude	42,000 ft	Static stability margin (Cajun)	13.1 in = 1.9 cal.
Cajun fin span	27.3	Maximum acceleration	58 G	Lift coefficient curve slope based on d^2 = 45.5 sq. in.), Cajun burnout	$C_1 = 0.13/\text{deg}$
Nike body diameter	17.0	Peak time	165 sec	Moment coefficient curve slope, Cajun burnout	$C_m = -.25/\text{deg}$
Nike fin span	54.0	Peak altitude Impact time Impact range	365,000 ft 330 sec 228,000 ft	Moment curve slope at Cajun burnout	$M = 410 \dfrac{\text{ft-lb}}{\text{degree}}$

Safety Considerations

Ignition of both the Nike and the Cajun propellant charges is accomplished by hot-wire squibs (Figure 3). The Nike employs four instantaneous ignition squibs; the Cajun, two 17-second time-delay squibs. Power for ignition is available only through switch S-1 located in the blockhouse. Closing S-1 applies power to the Nike igniter; however, relay K-1 prevents the application of power to the Cajun igniters until liftoff from the launcher de-energizes the relay by severing the cliplead "maypole" circuit. This prevents Cajun ignition should the booster fail to fire. In addition, a RF filter (consisting of C-1—C-5, R-1—R-7, L-1, and L-2) connected between the power source and the Cajun igniter prevents firing by extraneous RF voltages.

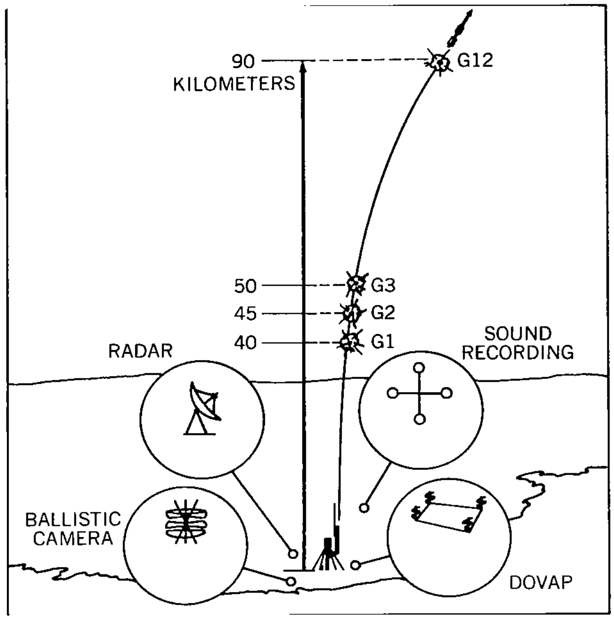


Figure 2—Rocket-grenade experiment.

Relation of Payload to Rocket

The rocket vehicle is composed of two distinct stages, shown in Figure 1. The first stage is the Nike booster which serves to lift the vehicle in the early moments of flight. Sitting on top of the Nike

Table 2

Wind-Weighting Factors Used for Nike-Cajun Grenade Shots from Wallops Island

Weight Table		Impact Range and Unit Wind Effect		
Altitude (feet)	Weight Factor	θ (degrees down from vertical)	Impact Range (n.mi.)	Unit Wind Effect (n.mi./fps)
50	.103	1	5.15	.910
90	.209	2	10.30	.910
150	.310	4	20.60	.910
200	.415	6	30.90	.910
400	.515	8	41.20	.910
700	.623	10	51.50	.910
1100	.700	12	61.80	.910
2300	.803	14	72.10	.910
5000	.880	16	82.40	.910
10000	.880	18	92.70	.910
20000	.880	20	103.00	.910
30000	.880			
32000	.879			
34250	.902			
36500	.935			
38750	.968			
41000	1.000			

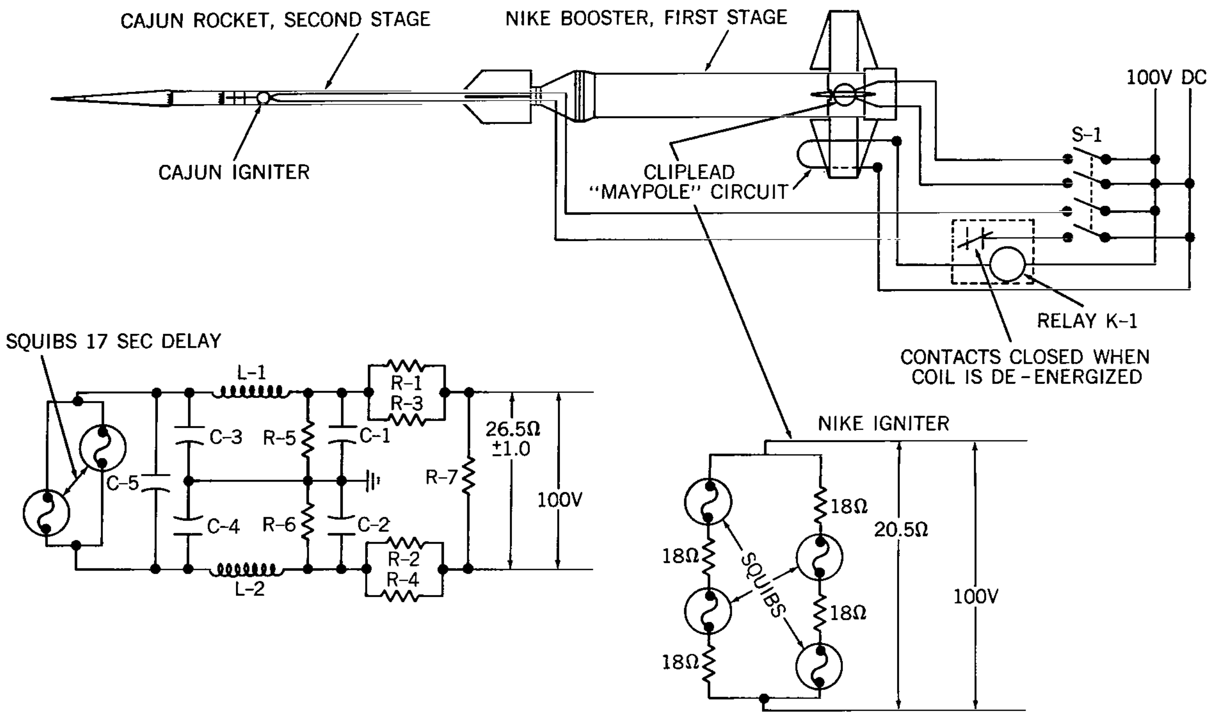


Figure 3—Nike-cajun rocket-ignition circuit.

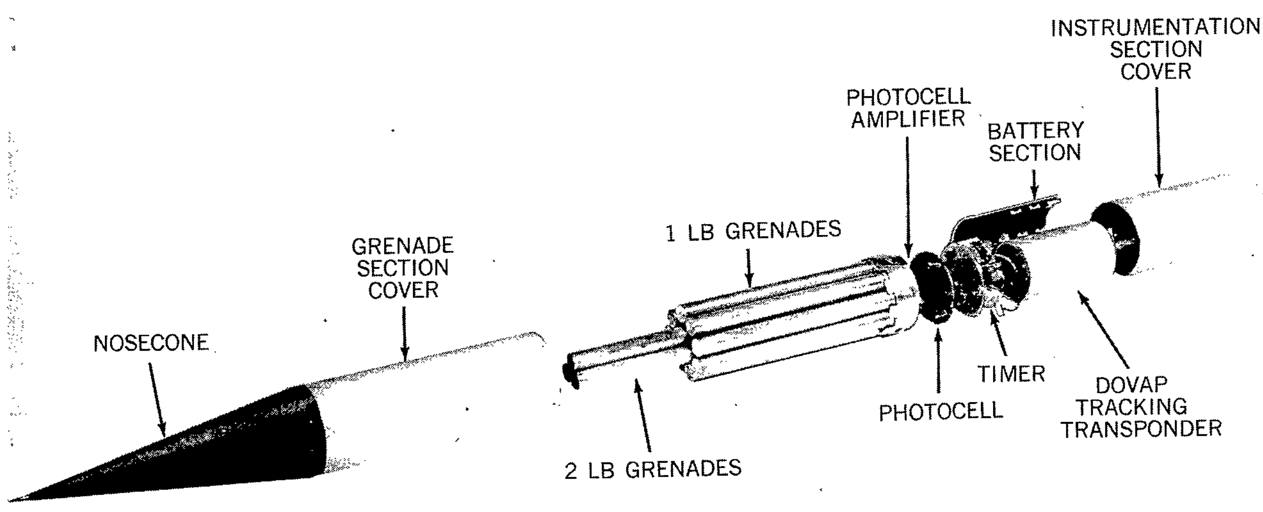


Figure 4—Payload structure.

is the second-stage Cajun rocket. The Nike booster drag-separates from the Cajun rocket after first-stage burnout, leaving the Cajun to carry the payload to the desired altitudes. The payload itself is positioned forward of the Cajun up to and including the nosecone. Information on aerodynamic bending of Nike-Cajun rockets due to oversize payloads is given in Reference 5.

Payload

The payload provides the means for accomplishing the objectives of the experiment. The payload structure consists of three units (Figure 4): Grenade section with nosecone; Timer and photocell assembly; and a DOVAP and battery section.

The nosecone, an 18-degree included-angle right circular cone, forms an integral unit with the cylindrical grenade section (Figure 5) which is composed of 12 cylindrical tubes held in place by plastic resin. One-pound high-explosive grenades fit into a peripheral ring of nine cylindrical tubes, and two-pound grenades fit in an inner ring of three tubes. The nosecone covering, a mixture of glue and asbestos through which each grenade breaks upon ejection, has the primary function of providing the proper aerodynamic configuration during the high-drag portion of the flight.

The timer and photocell assembly contains three infrared-sensitive lead sulfide (PbS) photocells, a photocell amplifier, and an electro-mechanical timer to provide for grenade ejection. The function of the photocells is to detect the flash of the grenade explosions.

The DOVAP and battery section contains the batteries furnishing power to the photocell amplifier and the timer, and a transponder which receives and retransmits the tracking signals emitted from a DOVAP transmitter on the ground.

Grenades

The grenades are cylinders 1-1/2 inches in diameter; the one-pound grenade is 18 inches long, the two-pound grenade is 28 inches long (Figure 4). Construction of the grenades is shown in Figure 6. The design is intended to produce a minimum of shrapnel upon explosion, in order to avoid serious damage to the rocket or instrumentation. Each grenade contains HBX-6 as the high explosive, an RDX booster charge, and a lead AZIDE detonator.

Grenade ejection is controlled by the timer described later in the text. Detonation is accomplished by a lanyard-operated device located in the bottom end of the grenade cylinder; the lanyard,

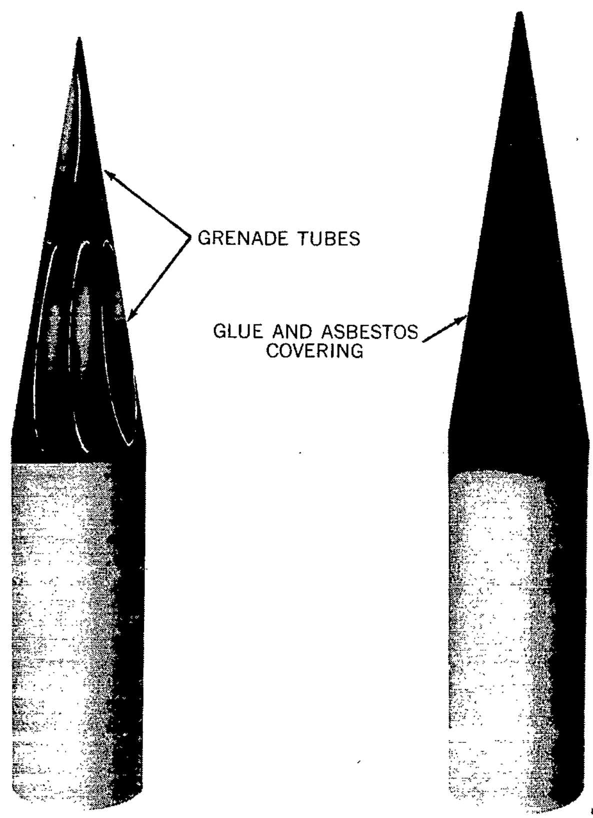


Figure 5—Nosecone/grenade assembly.

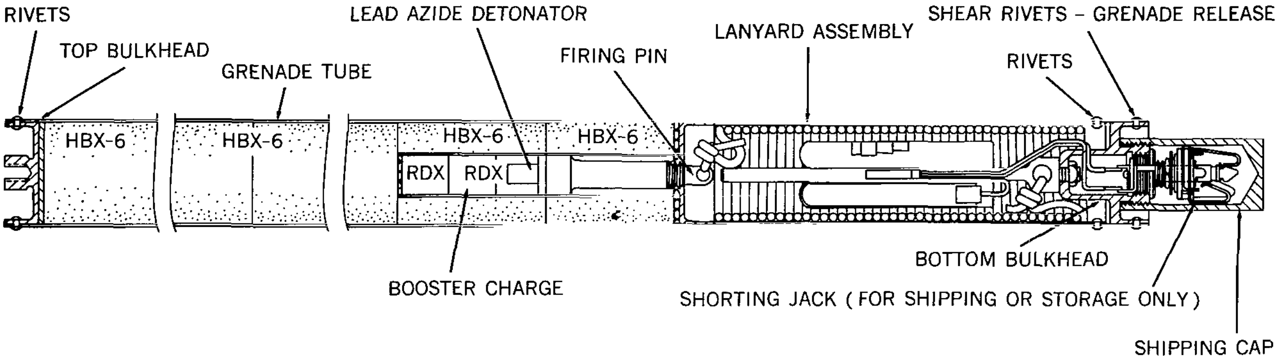


Figure 6—Schematic diagram of grenade.

14 feet long, is attached to the firing pin at one end and the grenade-assembly bulkhead at the other. The grenade is ejected by electrically detonating two 3-gram black-powder charges contained in the lanyard end of the grenade. Two powder charges are used, although either charge should provide sufficient force for successful grenade ejection. The ejection force shears the four soft retaining rivets and ejects the grenade through the nosecone covering. When the grenade has traveled 14 feet the lanyard pulls the firing pin which sets off the detonator, causing the RDX booster charge to explode; this in turn sets off the HBX-6 main explosive charge.

During 1960 and 1961, a number of grenade experiments failed because the whole payload exploded prematurely during early phase of the rocket flight. A laboratory study of the grenades to determine the cause of the detonations revealed that high vibration during burning of the Nike booster caused the RDX booster charge to pulverize at the surfaces of the pellets. The pulverized RDX sifted into the ejection cavity, where it could be detonated inside the payload as the black powder ignited. Steps were taken to reduce vibration and to increase the stability of the explosive, such as (1) bonding one explosive to the other to prevent chaffing; (2) introducing an "O" ring to prevent dust from entering the ejection cavity.

Timer

The timer (Figure 7), mounted on a ring located at the top of the DOVAP and battery section (Figure 4), controls the sequence of grenade ejection. It consists primarily of a timer motor, two Ledex switches (S-1 and S-2), and appropriate monitoring and safety circuitry. S-1 is a 12-position Ledex switch; S-2 is a 24-position Ledex switch. Receptacle J-2 and mating plug P-2 provide the connections for external control and monitoring of the timer positions before launch. Internal battery power is furnished through receptacle J-3 and plug P-3.

Receptacles J-7, J-8, and J-9 and plugs P-7, P-8, and P-9 prevent premature grenade firing by shorting the plus side of each grenade terminal to a ground. Connectors J-7 and J-8 and plugs P-7 and P-8 are disengaged after launch by the timer-motor operation several seconds before the first grenade is scheduled to eject. External-shorting plug P-9 (Figure 8), which serves as an additional safety short-circuit across the grenade terminals, is disengaged by pullout from J-9 during rocket launch. Receptacle J-5 and individual pin jacks provide electrical connections to the grenades.

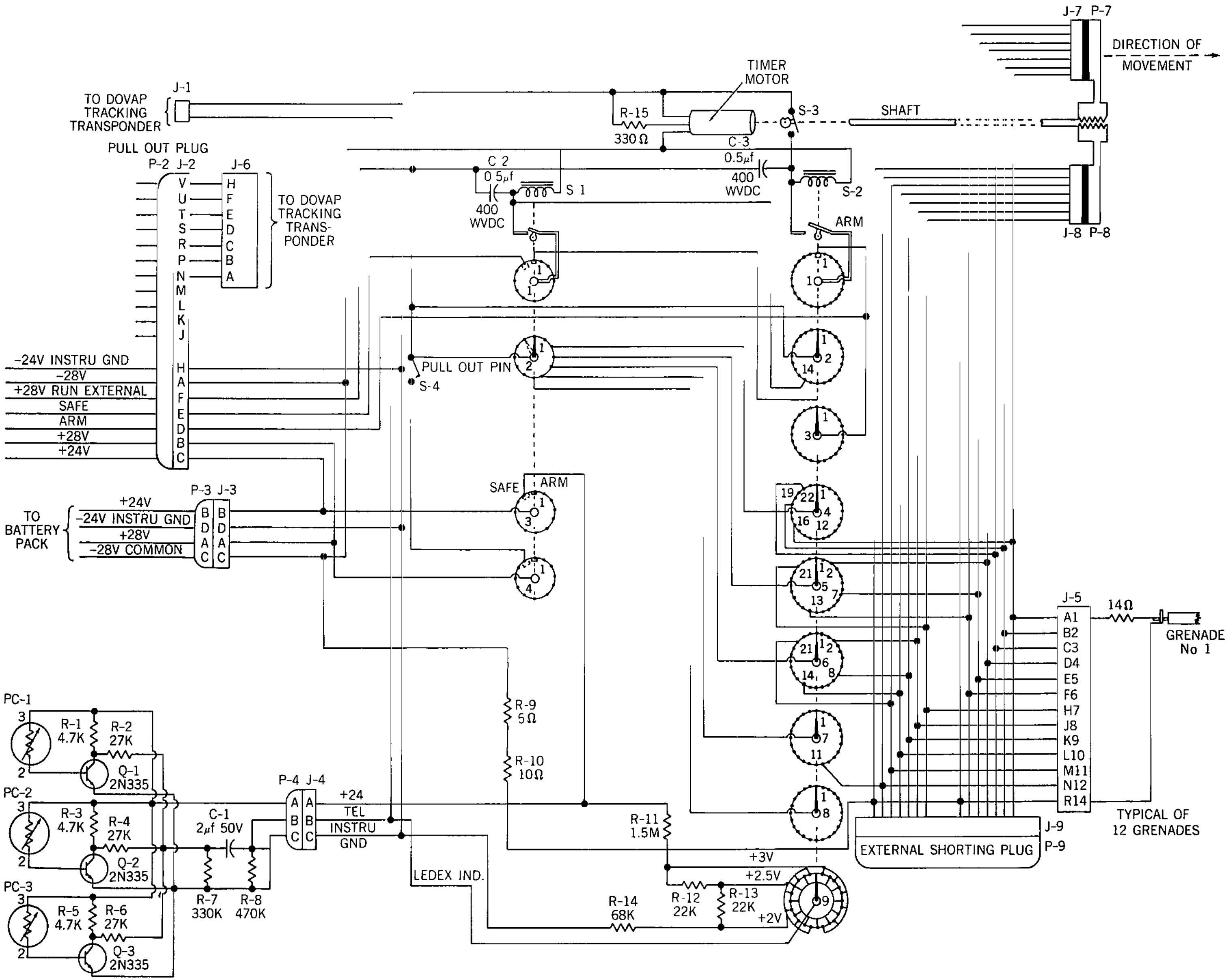


Figure 7—Schematic diagram of timer and photocell amplifier.

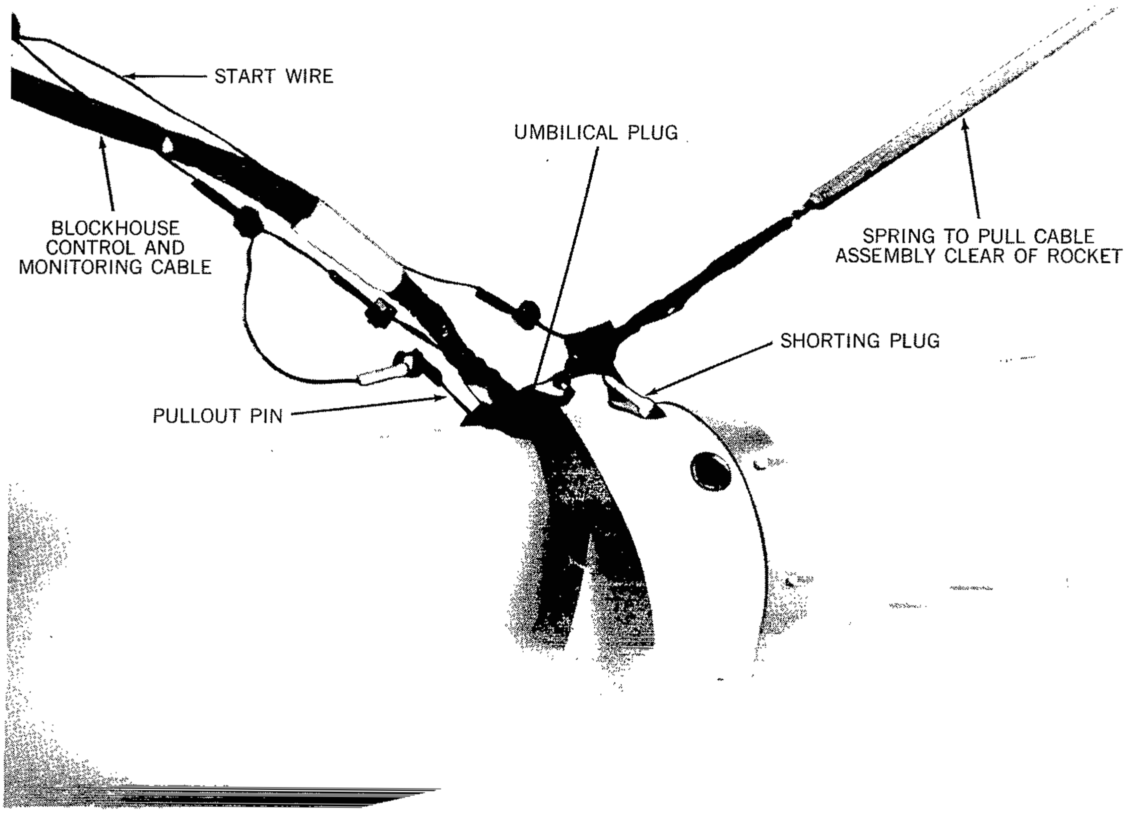


Figure 8—Prelaunch rocket connections.

J-4—P-4 and J-1—J-6 provide electrical connections to the photocell amplifier and DOVAP tracking transponder respectively.

As a third safety feature, accidental operation of the timer before launch is prevented by a pullout pin (Figure 8) which holds microswitch S-4 in the open position. This pin, attached to a start wire on the launcher, is disengaged by liftoff of the rocket. In addition, to ensure safety during handling and loading, the timer has a "safe" position which prevents inadvertent application of power to the timer.

Before the grenades are installed, the timer operation is checked as follows: (1) Apply +28 volts to pin E of J-2 to advance Ledex switch S-1 clockwise to the "safe" position; (2) Apply +28 volts to pin D of J-2 to advance S-1 to the "arm" position; and (3) Apply +28 volts to pin F of J-2 to energize the timer motor, advancing S-2 clockwise at one increment per second. Deck 9 of S-2, in conjunction with voltage divider R-11, R-12, R-13 and R-14, provides a voltage-step function, via J-4, P-4 and J-1, to the 30-kc subcarrier-oscillator (SCO) located in the DOVAP tracking transponder. This voltage modulates the telemetry output of the DOVAP, making it possible to monitor timer operation via the telemetered DOVAP signal; if the timer is functioning properly, the demodulated output should indicate a pulse train corresponding to Figure 9.

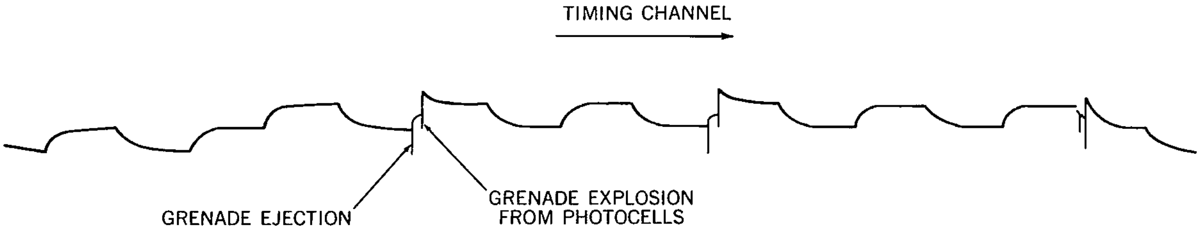


Figure 9—Timer operation pulse train.

To prepare the timer for grenade installation, the following steps are required: (1) Apply +28 volts to pin E of J-2 to advance S-1 to the "safe" position; (2) Apply +28 volts to pin D of J-2 to advance S-1 and S-2 to the "arm" position; at this time, deck 4 of S-1 applies +28 volts through pin B of P-4 and J-4 to the photocell-amplifier filaments; and (3) Apply +28 volts to pin E of J-2 to advance S-1 again to the "safe" position. (S-2 remains in the "arm" position.) Deck 4 of S-1 prevents application of power to the timer from either the remote source or the internal battery pack, making the timer safe for grenade loading. Two minutes before launch, power is again applied to pin D of J-2 to place both S-1 and S-2 in the "arm" position. Safety is maintained by the "start wire," the controlled switch S-4, and the grenade-terminal shorting plugs P-7, P-8, and P-9.

At launch, the motion of the rocket will disengage the umbilical plug P-2 (Figure 8) and cause the start wire to remove the pullout pin from S-4. The closing of S-4 energizes the timer motor, which in turn drives a notched cam that opens and closes microswitch S-3. Voltage pulses produced by the action of S-3 rotate S-2 clockwise one step per second. At +14 seconds S-2, deck 2, provides a pulse to S-1, causing it to advance clockwise by one increment. (The time of 14 seconds was selected because the rocket is not under power at this time, and the vibration is less severe.) At approximately +30 seconds of motor operation, the rotation of the threaded motor-shaft actuator disengages grenade-terminal shorting plugs P-7 and P-8 from receptacles J-7 and J-8. At +38 seconds (14 seconds +24 seconds), S-1 is again advanced by a pulse from S-2, deck 2; in this position, S-1 completes the circuit to deck 4 of S-2. At +40 seconds, deck 4 contacts close the circuit to grenade No. 1, causing it to be ejected and detonated. S-1 and S-2 continue to advance through each position until all 12 grenades have been fired.

DOVAP Tracking Transponder

The DOVAP T-10A tracking transponder (Figure 4) consists of a receiver, frequency-doubler, 2 watt transmitter, and 30-kc FM subcarrier-oscillator (Figure 10). It operates on power supplied by the rechargeable battery pack. The transponder, part of the Doppler tracking system, operates in conjunction with the ground stations to provide accurate velocity measurements essential in determining the exact position of the grenade explosions.

A continuous-wave 36.8-Mc signal is beamed to the transponder receiver from the ground transmitter. The received signal is doubled (73.6 Mc) by the frequency-doubler and retransmitted to the ground receiver. If the frequency received from the rocket were exactly twice the frequency of the ground transmitter, no relative velocity would exist between the ground receiver/ground transmitter

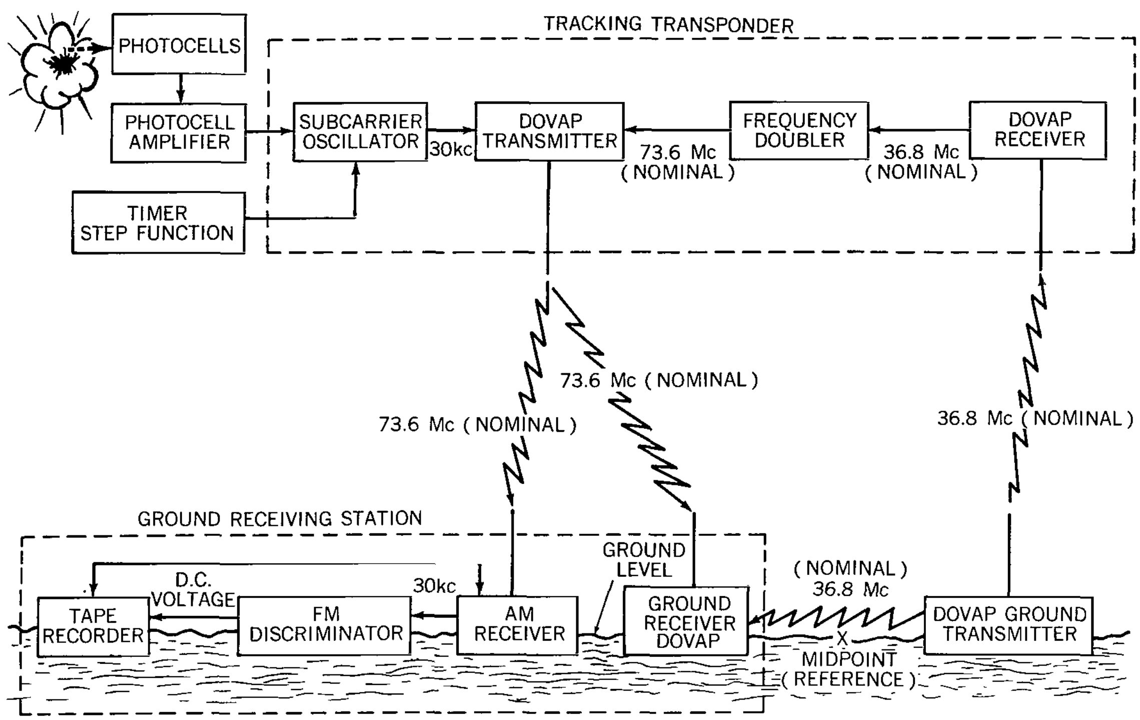


Figure 10—DOVAP tracking transponder operation.

midpoint and the rocket; the amount by which these two frequencies deviate from an exact value of two is a measure of the relative velocity between the rocket and the ground station. The frequency difference between the two signals is recorded by the ground stations for analysis after the flight.

The DOVAP transponder contains a single-channel telemetry system, consisting of a 30-kc ±15 percent FM subcarrier-oscillator used to amplitude-modulate the carrier. The frequency of the subcarrier-oscillator contains the telemetered information, consisting of amplified electrical signals caused by the response of the photocells on the rocket to the infrared light from the grenade explosions, plus a voltage-step function (Figure 9) which monitors grenade-timer switch positions (Figure 7).

Two pairs of antennas are used with the tracking transponder, one for transmitting and one for receiving. They are not included in the payload, but are attached to the propellant section of the second-stage rocket by means of steel straps (Figure 1). Each antenna is approximately 33 inches long by 2 inches wide, and protrudes from the rocket approximately 1-1/2 inches. Each antenna is covered by a molded glass-fiber housing to protect it from the flight environment.

Infrared Photocells and Telemetry Amplifier

Three infrared Kodak Ektron photocells (PC-1, PC-2, and PC-3) are located in three equally spaced ports 120 degrees apart on the side of the rocket, to detect the flashes of the grenade explosions. The photocells are connected to transistors Q-1, Q-2, and Q-3 of the photocell amplifier (Figure 7). The photocell amplifier operates on power supplied by a dry cell described later. The transistors offer a high-input impedance to the photocells, providing optimum coupling to prevent attenuation of the very small electrical signals generated by the grenade flashes. These flash signals are amplified and coupled through resistors R-2, R-4 and R-6 to a voltage-differentiating circuit composed of resistors R-7 and R-8 and capacitor C-1. A sharp differentiated pulse is applied to pin B of P-4 and fed to the SCO of the tracking transponder through receptacle J-1. The amplified signals modulate the 30-kc frequency of the SCO (Figure 10). In addition, deck 9 of S-2 provides a voltage-step function that reflects timer advances and modulates the SCO, allowing for continuous monitoring of the timer operation. The modulated SCO frequency, in turn, amplitude-modulates the DOVAP carrier frequency, permitting the intelligence to be transmitted to a ground station.

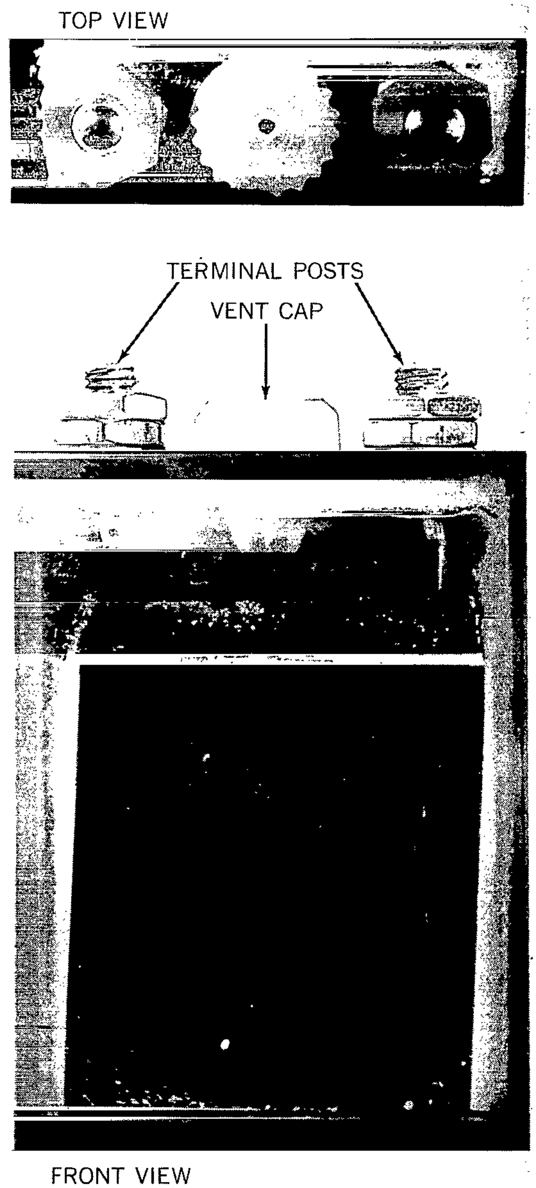


Figure 11—Silvercel battery.

Power Supply

Power requirements for the rocket-grenade experiment are furnished by three separate battery supplies. The timer and transponder equipment are powered by silver-zinc-alkaline batteries, the photocell amplifier by a dry-cell battery. A battery of five HR-3 silver-zinc cells located in the transponder section (Figure 4) supplies the approximately 8 volts required for transponder operation. Nineteen HR-1 silver-zinc cells, mounted in a ring encircling the transponder, furnish the timer with approximately 28 volts (Figure 4). One dry-cell battery provides approximately 24 volts for the photocell amplifier.

The silver-zinc-alkaline batteries are compact, lightweight, rechargeable Yardney HR-1 and HR-3 Silvercel* units (Figure 11). These units are high-rate discharge cells having a life expectancy of approximately 10 to 20 charge-discharge cycles or an average wet life of 6 months. Silver (+) and zinc (–) are employed as electrodes, with a strong solution of potassium hydroxide (KOH) as the electrolyte.

As the Silvercel units may swell slightly perpendicular to the electrode face upon servicing, it is recommended that the units be assembled in the battery containers before servicing. Complete servicing,

*Proprietary name for Yardney Co. silver-zinc-alkaline power units.

operation, and maintenance procedures are furnished with the batteries (Reference 6). Temperatures as low as $-55°F$ will not premanently harm the units, although prolonged exposure to temperatures above $110°F$ is harmful. The units are relatively free from hydrogen explosion hazards when used in closed, non-ventilated areas. However, sufficient hydrogen to cause an explosion can be generated by a defective or badly overcharged cell.

Flight Performance Instrumentation

During the initial phase of the experiment, flight-performance data were needed to assist in evaluating rocket problems. The performance instrumentation (Figure 12) was installed in place of the three center grenades; the rack shown in the photograph houses sensors and associated circuitry to measure the flight environment of the payload. Electrical output of these sensors is transmitted by the single-channel DOVAP telemetry. Time-sharing of this telemetry is accomplished by a 24-segment commutator rotating at 10 revs/sec.

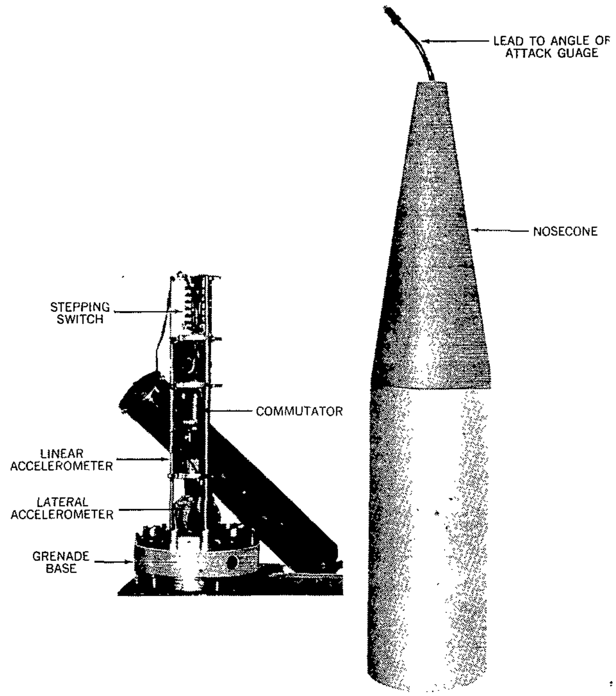


Figure 12—Flight performance instrumentation.

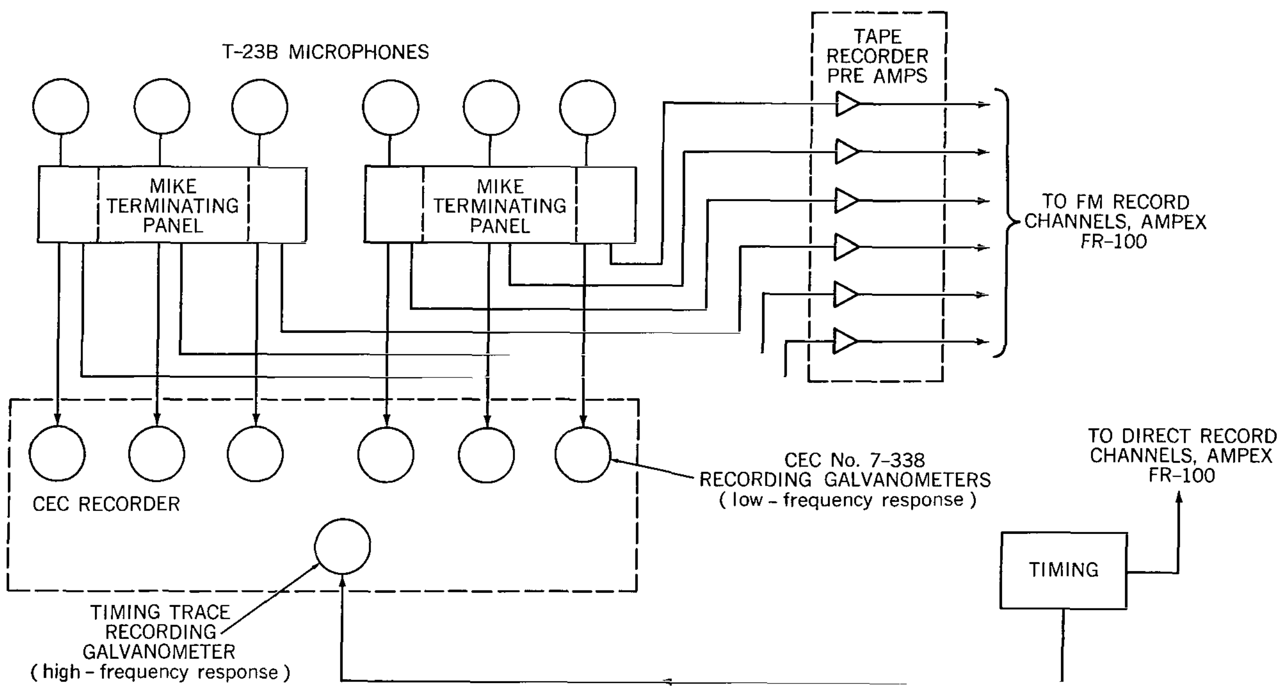


Figure 13—Block diagram of sound-ranging system.

Parameters most frequently monitored during these tests were nosecone temperature, axial acceleration, vibration, and angle of attack. The resulting data were used to evaluate grenade-ejection problems, payload variations, and possible modifications.

Ground-Based Instrumentation

Sound-Ranging System

A block diagram of the sound-ranging system is shown in Figure 13. References 7 and 8 describe the instrumentation, installation, operation, and research activities required for a typical experimental sound-ranging system. The system consists of at least five microphones (arranged in a symmetrical pattern, as shown in Figure 14), a recording oscillograph, a tape recorder, and appropriate amplification, timing, and interconnecting circuitry. The microphones are modified U. S. Army Signal Corps Type T-23B, a hot-wire suitable for sound-ranging because of its sturdiness and low-frequency response. The microphones should be—as nearly as possible—in a horizontal plane; the distances between them should be nearly equal and approximately 400 m. Figure 15 shows the physical appearance of the microphone, and Figure 16 is a schematic diagram of the microphone as modified for this application. To reduce noise level due to wind and atmospheric pressure fluctuations, the microphones are mounted below ground level and covered by a large canvas screen and a wooden baffle plate. Figure 17 shows typical microphone-installation requirements. A terrain vegetated with underbrush or trees several feet high shielding the ground surface uniformly from the wind is best suited for this installation.

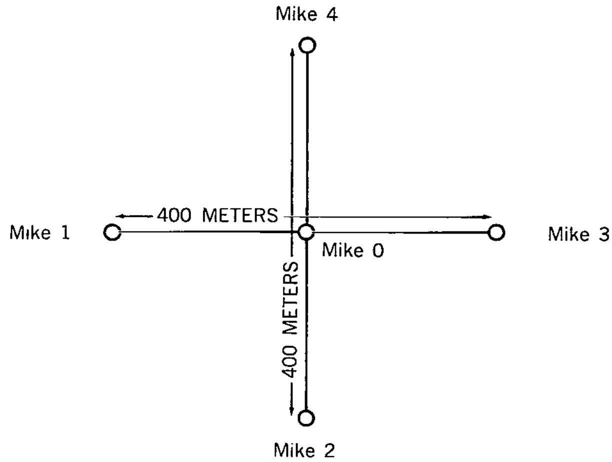


Figure 14—Microphone Array.

The oscillograph, a Consolidated Engineering Corporation 5-119, 36-trace mirror-galvanometer type, records by means of a light beam reflected on a moving strip of sensitized paper. It serves as a backup recorder and also provides an immediately available record of events. A typical record is shown in Figure 18. An Ampex

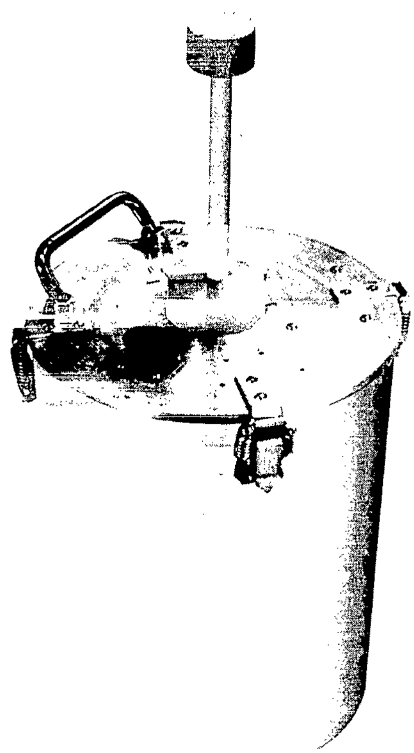


Figure 15—T-23B microphone.

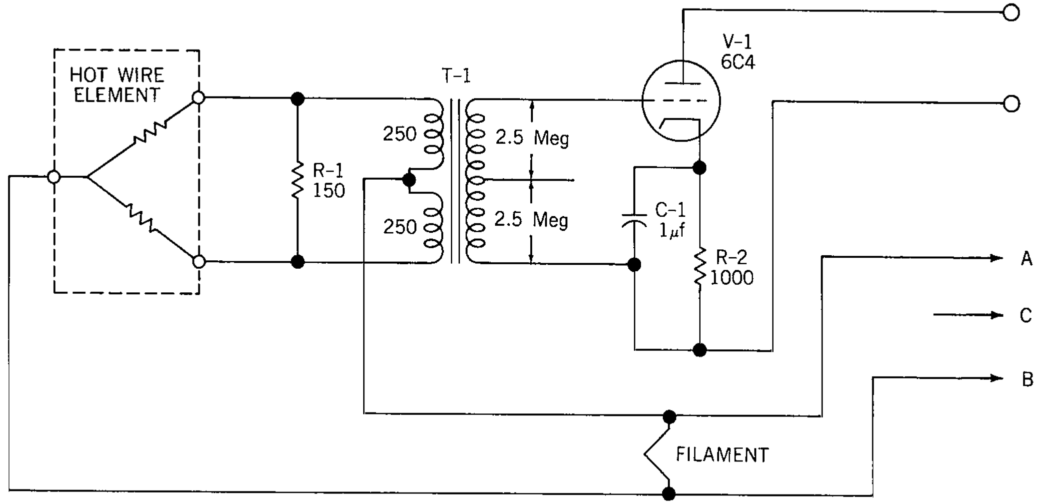
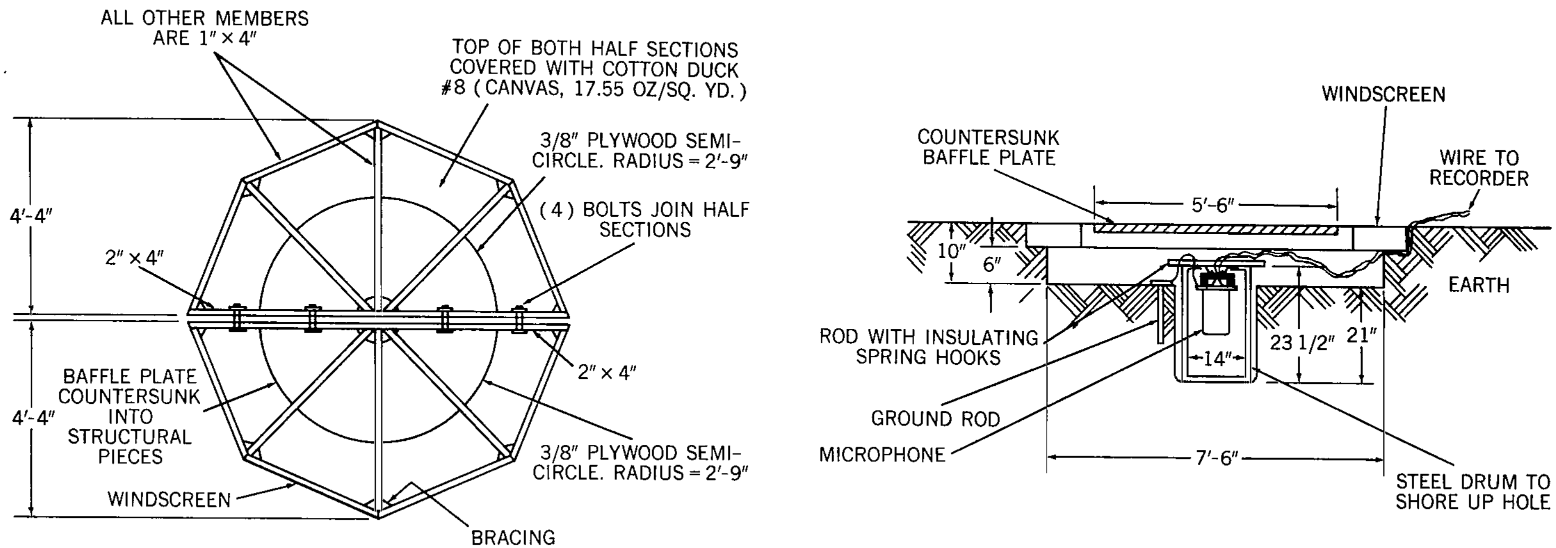


Figure 16—Schematic diagram of modified T-23B microphone.



(a) Bottom view

(b) Side view

Figure 17—Microphone ground installation.

FR-100 multichannel tape recorder is used as a primary recorder. The low-frequency (4-20 cps) output signals from the microphones are recorded by means of the tape recorder's FM record electronics. For exact analysis of the low signal-to-noise acoustic waves generated by the higher altitude grenade bursts (above 70 km), the tape records may be played back through a bandpass filter peaked at the optimum frequency (approximately 4 cps).

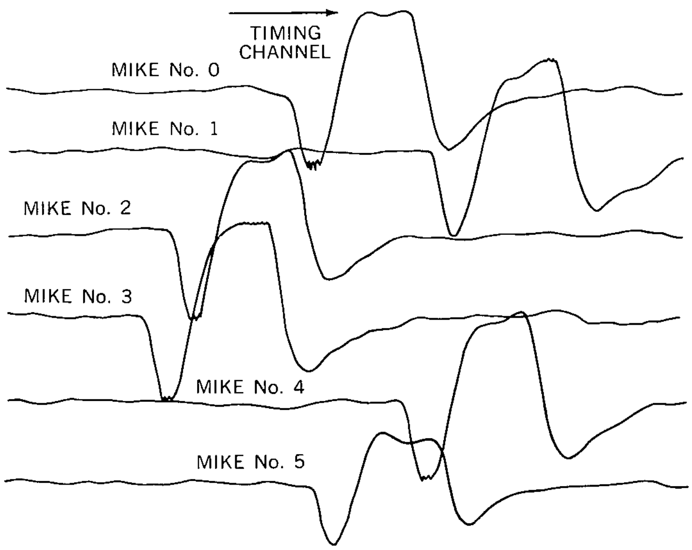


Figure 18—Typical sound-ranging record.

Accurate timing is provided by a Beckman/Berkley type 7360 timer or other suitable means. Filament power is furnished by a pair of series-connected 12-volt automobile batteries; plate power for the microphone plate circuit is furnished by a Lambda Model 29 regulated power supply. A separate power supply is used for each microphone circuit to eliminate crosstalk.

The microphones are connected to two microphone terminating panels, three to each panel (Figure 13). The terminating panel contains an array of dc amplifiers that provide impedance matching and input signals to the oscillograph and the tape-recorder preamplifiers; the dc amplifiers match the microphone impedance to a regulated 28 ohms, providing a balanced line to the recorders. The output of each microphone is recorded as a separate trace on the photographic paper. The dc amplifiers also decouple the B+ voltage from the galvanometer circuit.

Ground Flash Detector

A ground flash detector, consisting of a lead sulfide photocell mounted behind a germanium filter at the focal point of a parabolic mirror, is capable of detecting the grenade bursts even in daylight. The mirror axis is pointed in the direction of the anticipated grenade explosions to permit the photocell to detect the emitted infrared radiation. Since the instrument encompasses a field-of-view of approximately 20° × 20°, it can detect all explosions without change of orientation. The output of the photocell is recorded along with a timing trace to constitute an accurate record of the time of each grenade explosion. The disadvantage of this system, as with any optical or sight system, is that a clear sky is required in the vicinity of the rocket's trajectory. In the present series of grenade experiments, therefore, it is used only as a backup to the rocketborne flash-detector system described previously.

Telemetry

The telemetry data is received on the ground by recording the demodulated Doppler tracking signal. The telemetry ground station consists of an AM receiver, an FM discriminator, and a tape recorder. The single-channel telemetry data containing grenade-flash times and timer-performance information is received in the form of an amplitude-modulated 73.6-Mc DOVAP signal. The AM receiver detects the frequency-modulated 30-kc intelligence from the 73.6-Mc carrier, transmitted by the DOVAP transponder, and feeds the 30-kc ±15 percent subcarrier signal to the discriminator where it is demodulated. This results in the voltage signals shown in Figure 9. The voltage signals are recorded by oscillogram, and the 30-kc subcarrier wave is recorded on magnetic tape.

Tracking

The DOVAP System, a continuous-wave tracking system utilizing the Doppler-frequency shift, provides a highly accurate method of determining the position of each grenade explosion by integrating the velocity of the rocket over the whole flight path. The rocket-grenade experiment can use DOVAP tracking in any of three combinations:

1. Three or more DOVAP receiving stations (Reference 9);
2. Single-station DOVAP (SSD) receiver with interferometer antenna array (Reference 10); or
3. Single-station DOVAP receiver using conventional antenna in conjunction with a ballistic camera (Reference 11).

In each instance, a continuous-wave transmitter of approximately 1 kw power is also required.

The following paragraphs describe the various DOVAP tracking systems; References 12, 13, 14, and 15 describe DOVAP data-reduction methods.

The Multistation DOVAP System consists of a transmitting station and at least three receiving stations. Each receiver uses the Doppler shift to define an ellipsoid surface through the rocket vehicle. The intersection of these three surfaces determines the vehicle position. At each DOVAP ground receiver, continuous comparison is made between two radio signals from the ground transmitter; one signal is transmitted directly to the receiver, the other is transmitted to the receiver via the rocket. Figure 19 shows a typical transmitter-rocket-receiver path for these systems. A nominal 36.8-Mc signal is sent to the rocket; its frequency is doubled (73.6 Mc) and retransmitted to a receiving station. The station has two receivers, one receiving the doubled-frequency signal from the rocket; the other receives the signal directly from the ground transmitter and doubles the frequency *after* reception. The signals are heterodyned, and the difference-frequency is obtained. The signal sent via

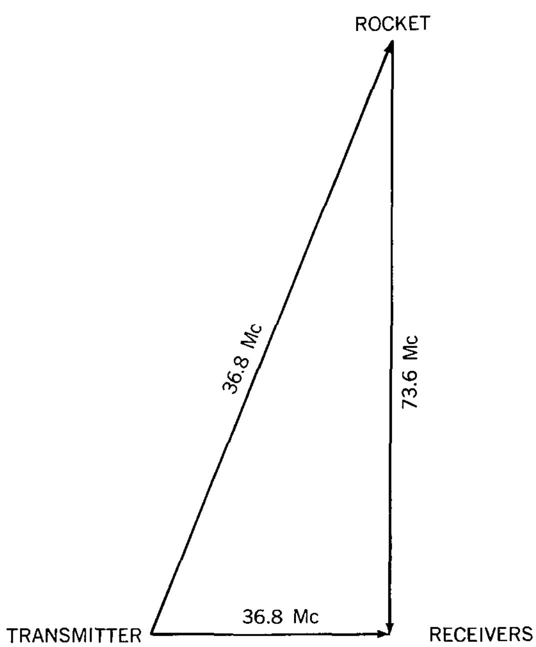


Figure 19—Typical transmitter/rocket receiver path.

the rocket generally experiences a Doppler shift due to the rocket's motion; thus, the difference in frequency obtained between the two receivers at the receiving stations is proportional to the time-rate of change of the transmitter-rocket-receiver path length. The known transmitter-receiver distance remains constant. Integration of the difference-frequency over the time of flight determines radial distance to the rocket.

A block diagram of a typical ground station is shown in Figure 20. An operational ground station generally uses two receivers to receive the 73.6-Mc signal from the rocket; one receiver operates through a lefthand circularly polarized helical antenna, the other through a righthand one. Each of the signals is independently heterodyned with the ground-transmitter signal, in order to obtain a measure of the component of the Doppler shift introduced by the roll of the rocket. The difference frequencies (resulting from heterodyning the signals from each helical antenna with the original signal) are recorded on magnetic tape along with a timing signal.

The difference frequencies are integrated over time for each receiver; by comparing the results produced by the lefthand and righthand polarized antenna at one station, the rocket's position can be defined as the surface of an ellipsoid of revolution whose foci are located at the receiving and transmitting stations respectively. If this integration is performed manually, it requires accurate counting

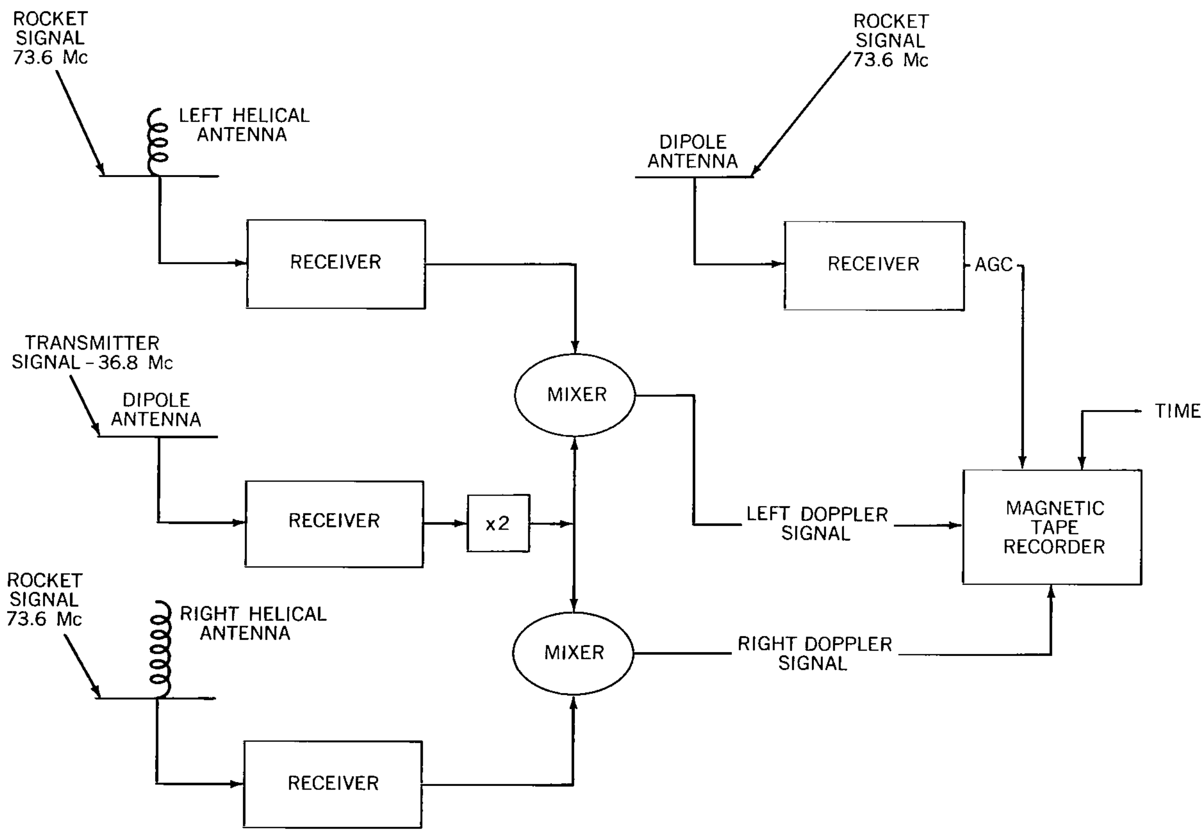


Figure 20—Four-station DOVAP instrumentation.

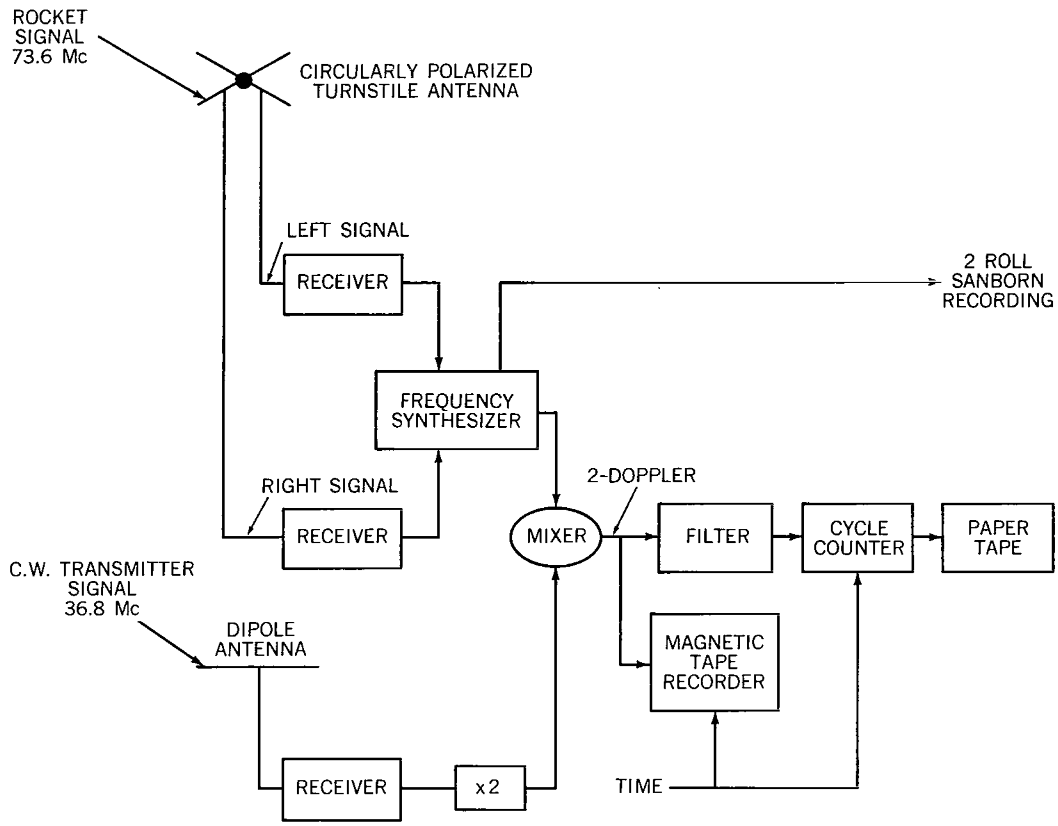


Figure 21—Single-station DOVAP (SSD) instrumentation.

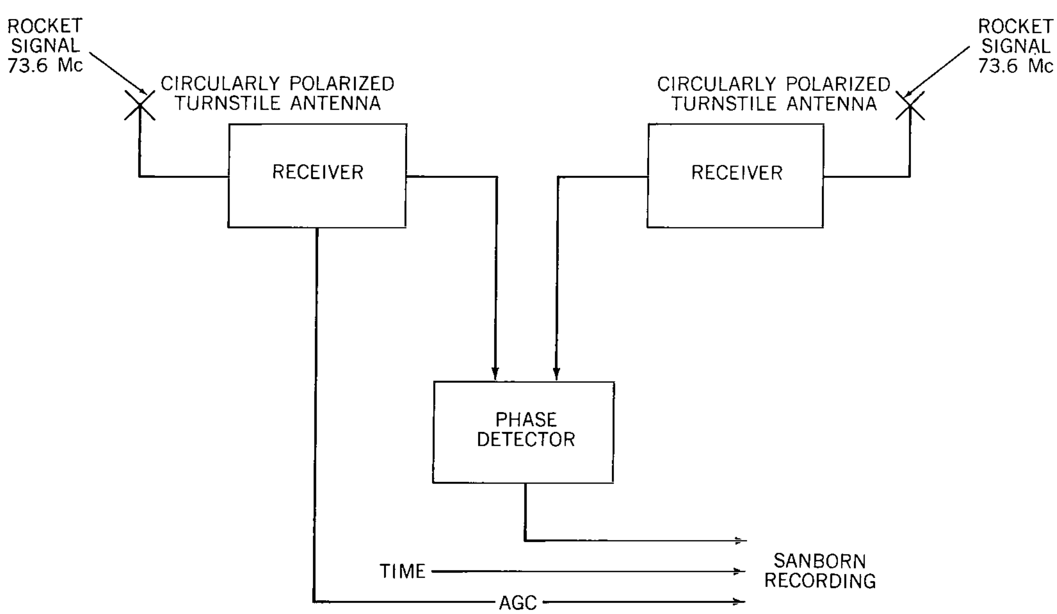


Figure 22—Continuous-phase interferometer instrumentation.

of about 80,000 cycles for each receiver up to the peak altitude of the rocket—in the case of a 4-station experiment, 640,000 cycles. Three receiving stations (the intersection of three ellipsoids) theoretically will provide information sufficient to pinpoint the position of the rocket at any time; operationally, however, at least four stations are used, to statistically improve the accuracy of the solution. The accuracy of a four-station system is generally better than ±15 meters with the rocket at an altitude of 90 km. Disadvantages of this system are the long baselines required between receivers (20-30 km) and the large number of cycles to be counted.

The DOVAP system yields the position of the center of the transponder antennas rather than of the grenade explosion. The grenade is designed so that the explosion occurs within less than 5 meters from the rocket, a negligible distance, and the location of the transponder antenna at the time of the grenade explosion can therefore be taken as the position of the explosion. In addition, roll rate of the rocket can be measured from the periodic fading of the signal received through a simple dipole antenna.

The Single-Station DOVAP (SSD) rocket-tracking system uses the Doppler effect measured at one receiving station to define one ellipsoidial surface, and a square array of antennas to define the direction cosines to the rocket by means of interferometer techniques. The Doppler frequency is obtained by the method described previously. The receiving station automatically compares the phase of the signals received at each antenna, and the direction cosines as well as the roll correction are thus determined electronically without resort to manual techniques. The SSD therefore eliminates the disadvantages of the multistation DOVAP mentioned above.

Figure 21 illustrates the instrumentation plan of the single Doppler-receiver station. A single circularly polarized turnstile antenna, instead of the lefthand and righthand helical antennas of the multistation DOVAP, is used to receive both the lefthand and righthand signals; the resulting signal is heterodyned with the doubled transmitter signal to produce twice the Doppler frequency, which is recorded on magnetic tape. In order to obtain a "quick look" at the range component of the trajectory, the signal is also fed through a tracking filter into an automatic cycle-counter that produces lists of cycle counts and time on paper tape.

The SSD system uses two continuous-phase interferometers, each of which measures and records a phase difference in the arrival of the signal from the rocket at two ground-receiver antennas. The instrumentation of the interferometer is shown in Figure 22. Two ground-receiver antennas located 214 feet apart in the north-south direction and two receiver antennas located 214 feet apart in the east-west direction (all located in a horizontal plane) form the interferometer antenna array. The SSD receiver is located in the center of the array (Figure 23).

The signal from the rocket is considered to be a plane wave; the normals to the wavefront through the receivers can be considered as ray paths along which the signal has a sinusoidal variation. The ray paths from the rocket are parallel as they arrive at each pair of receivers. The signal is received at each receiver antenna, amplified, and combined in a phase detector which measures the difference in electrical phase of the two received signals. A recording is made of the phase difference between the output of each pair of receivers. The phase differences are a direct measure of the direction

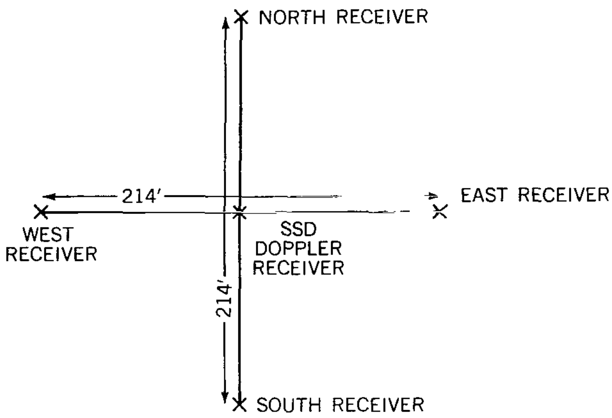


Figure 23—Single-station DOVAP antenna array.

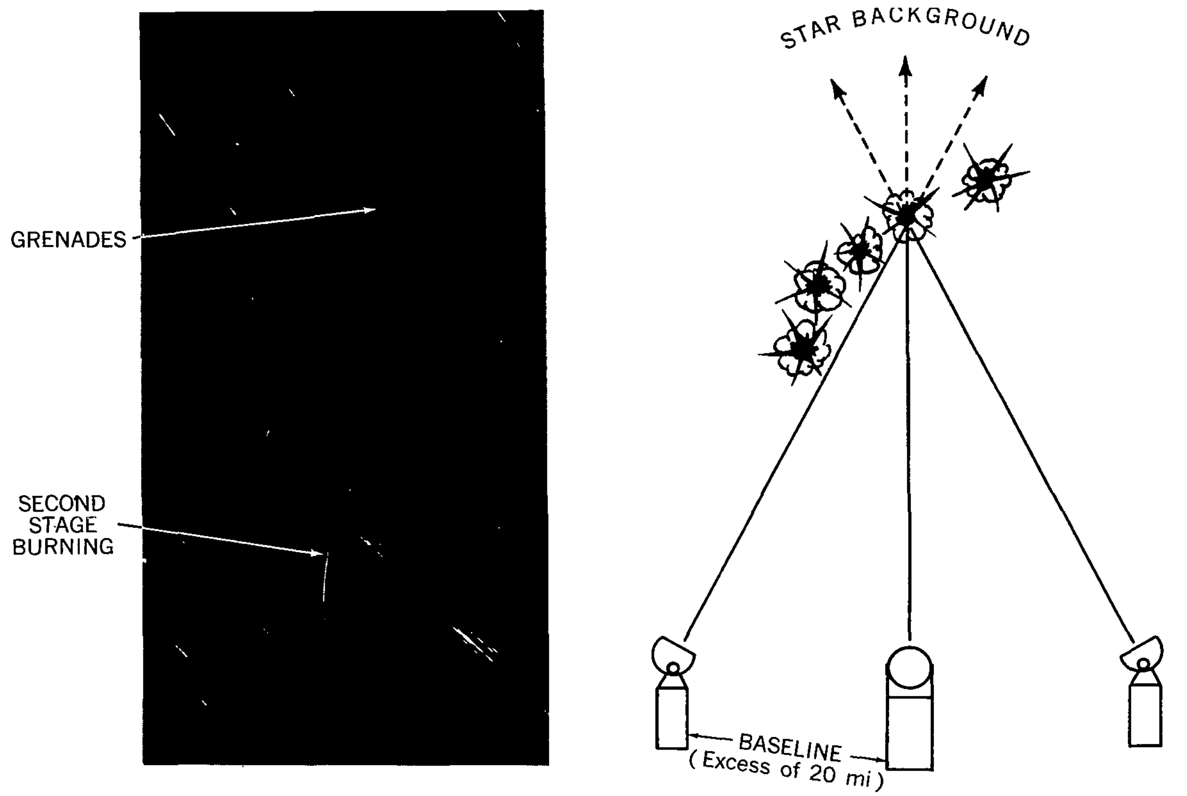
cosine of the wavefront. The accuracy of this system is comparable in the radial component to the accuracy of the multistation system, but is less in the direction cosines.

The Single-Station Doppler Ballistic Camera system consists of a single receiver station with one lefthand and one righthand circularly polarized helical antenna, and a ballistic camera. The light from grenade bursts is recorded on the photographic plate of the ballistic camera. This system can be used only at night when the sky is clear; its use is therefore limited by severe time restrictions on the conduct of the experiment.

The ballistic camera, a fixed-plate camera with a field-of-view of about 60 degrees, is mounted with its optical axis pointed in the direction of the expected grenade explosions. Time exposures of f/8 or f/11 on infrared-sensitive plates (Kodak F-103) are generally used. Immediately before and after a rocket flight, an image of the star background obtained with a series of precisely timed exposures (within 0.1 sec sidereal) is taken on the same plate with the camera positioned precisely as for the rocket flight. The star trails with known celestial coordinates serve to determine the direction of the optical axis of the camera. Direction cosines for the grenade explosions can be derived by measuring the positions of the grenade-flash images relative to the star trails; the direction cosines from the ballistic camera for each flash of light define a straight line passing from the camera location to each flash. The range sum derived from the Doppler-cycle count at each flash time defines an ellipsoid of revolution, with foci at the transmitter and receiver and with the major axis equal to the range sum obtained from the cycle count, the flash position being located on the surface of the ellipsoid. Each flash position is obtained by solving for the intersection of the ellipsoid and the given straight line, the solution representing the space positions of the light flashes (Reference 16).

Ballistic-Camera Tracking. A minimum of two ballistic cameras will provide an accurate and sufficient method of determining grenade-explosion positions in experiments that do not employ electronic-tracking systems. Grenade-explosion positions are determined by locating two or more ballistic cameras along a baseline exceeding 20 miles (Figure 24); each camera is positioned to photograph the grenade bursts against a known star background. Grenade-burst coordinates are obtained by determining direction cosines to the grenade explosions at each camera site and intersecting the lines-of-view. Although only two cameras are necessary, an array of four is generally used to improve the statistical accuracy of the solution. Disadvantages of this method of determination are the requirements for night operation, the need for clear weather, and the baseline length required between cameras for accurate measurements.

Radar Tracking, an alternate means of obtaining rocket trajectory, is ordinarily used in conjunction with, and as a supplement to, other tracking systems; however, if sufficiently accurate, it may be used to determine grenade-explosion coordinates. Several radar data-acquisition systems are



(a) Portion of ballistic camera plate (b) Cameras photographing against star background

Figure 24—Ballistic camera tracking.

used to perform various functions in the rocket-grenade experiments. These systems include: permanently installed (modified) SCR-584 radar; mobile (van-mounted) SCR-584 radar; Mod II SCR-584 radar (extensively modified); AN/FPS-16 radar; and long-range S-band radar (SPANDAR). In addition to the data-acquisition radar systems, an AN/FPS-12 medium-range surveillance radar is used for range-safety clearance (sea and air traffic). Functions and principal characteristics of the various data-acquisition radar systems are described in the following paragraphs; additional details may be found in Reference 17.

The SCR-584 radar systems are essentially World War II gun-laying S-band radar systems modified for missile tracking. The permanently installed SCR-584 modifications include automatic range tracking, increased output power, a larger antenna reflector, a data-recording system, a boresight camera, and a master-slave range system. The system operates over a frequency range of 2,800 to 2,900 Mc with a normal peak power output of 400 kw. The maximum beacon-tracking range (using an active radar beacon on the rocket) is 384,000 yards; the maximum skin-track range (no active radar beacon) is 62,000 yards (for a 1 m^2 target).

The mobile SCR-584 is essentially standard, the only modification being a change in the range system to include automatic range-tracking at a maximum range of 96,000 yards. These radar systems are used to obtain backup data during early portions of rocket flight. Their main purpose is to provide acquisition data and designation for other higher precision radars.

The Mod II SCR-584 is extensively modified and rehabilitated to perform automatic angle- and range-tracking. Mod II improvements include dual local oscillators for skin and beacon track, A-scope range presentation, intermediate servosystem for smoothing purposes, tunable S-band magnetron, output-power attenuation, multipulse and coding capability, vertical or horizontal polarization, and pulse-repetition frequency selection. The Mod II operates over a frequency range of 2,700 to 2,950 Mc with a normal peak power output of 250 kw. Maximum beacon-track range is 768,000 yards; skin-track range is 14,000 yards.

This radar provides recorded data as follows:

1. Synchro voltages: representing slant range, azimuth, and elevation angles

2. Potentiometer voltages: representing slant range, and sine and cosine functions of azimuth and elevation angles

3. Precision digital data: representing slant range, azimuth, and elevation angles.

The Mod II provides real-time position data for range safety, and acquisition data for other equipment. Like the SCR-584, its accuracy is not sufficient for position determination of the grenade explosions.

The AN/FPS-16 radar is a high-precision C-band monopulse tracking radar designed and built for missile-range instrumentation. The AN/FPS-16 is the only radar described here that is sufficiently accurate to determine grenade-explosion coordinates. The AN/FPS-16 has a frequency range of 5,400 to 5,700 Mc with a tunable magnetron, and a fixed frequency of 5,500 Mc with a fixed magnetron. Normal power output, using the tunable magnetron, is 250 kw, or 1 megawatt with a fixed magnetron. The system has a maximum beacon-tracking range of 1,000 km and a skin-track range of 260 km (with a 1 m^2 target).

The AN/FPS-16 radar, in addition to synchro and potentiometer voltages and precision digital data, provides real-time present-position analog data for use in range safety.

The Long-Range S-Band Radar (SPANDAR) is a high-power conical scan-tracking radar employing a 60-foot parabolic reflector. The system has a frequency range of 2,700 to 2,900 Mc with a peak power output of 5 megawatts. The beacon-tracking range is 8,000 km, and the estimated skin-tracking range (for a 1 m^2 target) is 1000 km.

The system includes a parametric amplifier in the receiving system and digital-data system. As a backup, it is used in conjunction with other tracking equipment in the rocket-grenade experiment.

METHOD

General

In the rocket-grenade experiment, average atmospheric temperatures and winds for the interval between two high-altitude grenade explosions are determined by measuring exactly the time when each grenade explodes, the time when each soundwave arrives at various ground-based microphones, and the position of each grenade explosion. The method can be expanded to $n - 1$ data points for n explosions: thus, the greater the number of grenades carried aloft by the rocket, the greater the number of data points for determining temperatures and winds.

Besides the initial parameters—angles of arrival of the sound wavefront at the center of the ground-microphone array; the times of explosion of the "upper" and "lower" grenades; and the position coordinates of these grenades—certain additional data must be available to facilitate the computation of temperatures and winds. These are: a measurement of temperature (within $\pm 0.25°C$) at the ground in the vicinity of the microphones; the surface-wind vector in the same area (within ± 2.5 m/sec); as well as standard radiosonde observations of temperature in the general area of the experiment, up to about the altitude of the lowest grenade. If, in addition to this, a measurement is available of pressure or density at the surface, profiles of pressure and density may be calculated up to the altitude of the highest grenade explosion. An exact geodetic survey of all ground-station locations is also required.

The location of each microphone in relation to all others must be known within ± 0.2 meters. The precision of the survey for the other (nonacoustic) ground system varies with the tracking system used, but generally the relative location of each element of each tracking system (for example, DOVAP antennas) must be known within ± 0.5 meters. As the DOVAP tracking system in particular operates on the principle of tracing the rocket's trajectory back to its origin (the launcher), the rocket launcher must be included in this survey.

If a ballistic-camera system is used, an absolute survey is required in addition to the relative one mentioned above; the position of each camera must be known within about 30 seconds of latitude and longitude. An absolute time measure must also be provided (within ± 0.1 sec) during exposure of the star trails. For all other systems, relative timing must be provided at all recording stations, with a precision of 0.005 sec over the period from launch to the time of soundwave arrival (usually 500 sec), and with a precision of 0.0005 sec at the sound-ranging station only during the period of each soundwave arrival at the microphone array (usually 1 sec).

Determination of Initial Parameters

Times and Positions of Explosions

The times of grenade explosions are read directly off the records of the rocketborne or ground flash-detector outputs. Once these times are known, the grenade coordinates may be read off or interpolated from trajectory tables produced by the various tracking systems. If FPS-16 radar tracking is used, the trajectory can be obtained in the form of punched cards or digital magnetic tape;

for all other tracking systems, more or less laborious manual steps (such as reading ballistic-camera plates or integrating DOVAP cycles) will be necessary to produce a trajectory (refer to section on tracking).

Angles of Arrival of Soundwaves

Direction cosines of the sound wavefront are mathematically derived from the times of arrival at each microphone. These times are read off the sound-ranging records. Since the position of each microphone is known, a plane or spherical wavefront is analytically fitted through the set of space-time microphone coordinates.

A least-square solution for a plane wave may be derived from the arrival times and coordinates of more than 3 microphones. An array is shown with the wavefront at time $t = 0$ passing through the microphones in Figure 25. Microphone 0 is chosen as the origin of the righthand Cartesian coordinate system. All coordinates and times are referenced to microphone 0, and it is assumed that the time of passage of the wavefront through microphone 0 is measured precisely. The distance r_i from microphone i to the wavefront should thus be: $r_i = c_0 t_i$ where t_i is the observed time of arrival of the soundwave at microphone i and c_0 is the speed of sound on the ground. The direction cosines for the wave normal can be obtained from a least-square bit of the wavefront tangent to all spheres r_i.

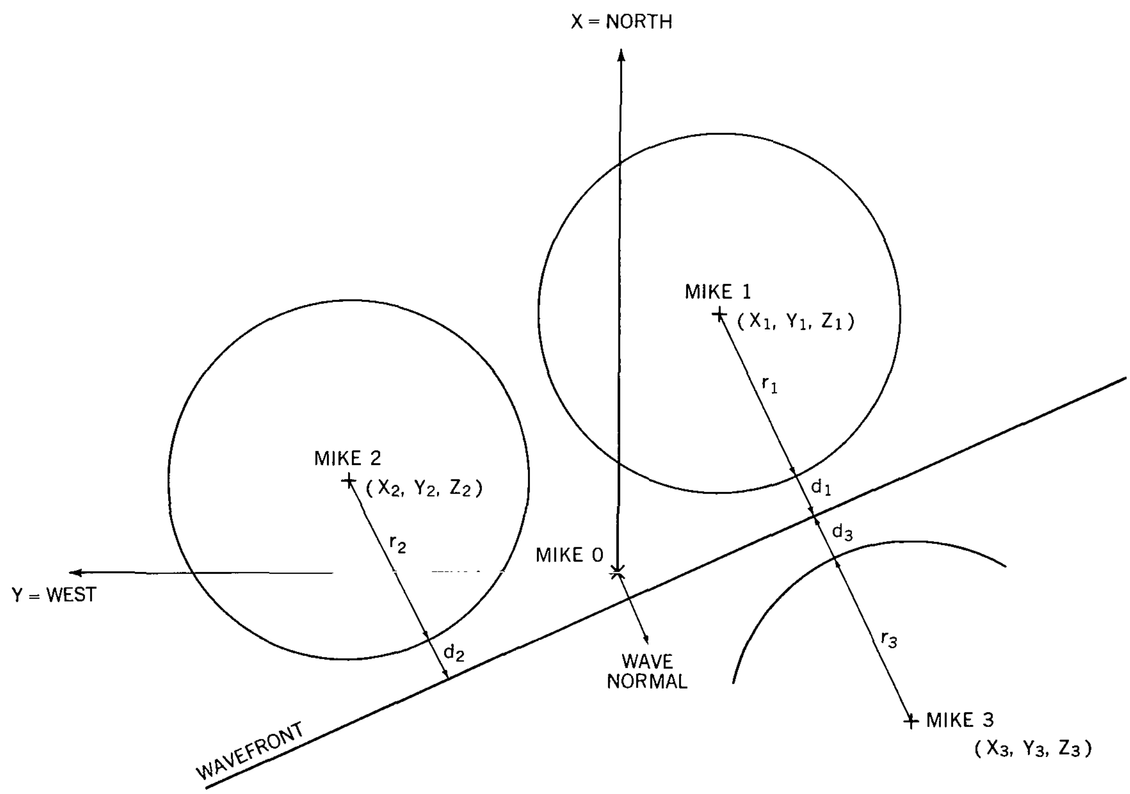


Figure 25—Pictorial representation for fitting the wavefront.

The normal equations of the least-square solution are obtained from the following analytic expression for the distance d_i between the plane wavefront and the surface of a sphere of radius r_i around microphone i with the coordinates $(X_i Y_i Z_i)$; d_i is measured along the direction of the normal to the plane:

$$d_i = X_i \alpha + Y_i \beta + Z_i \gamma - r_i, \tag{1}$$

where ($i = 1, 2, ..., 5$) and α, β, γ are the direction cosines of the wave normal. The best fit for the plane wave is obtained when the sum of the squares of the distances d_i is a minimum; i.e.,

$$\frac{\partial \Sigma d_i^2}{\partial \alpha} = \frac{\partial \Sigma d_i^2}{\partial \beta} = 0, \tag{2}$$

Since

$$\alpha^2 + \beta^2 + \gamma^2 = 1, \tag{3}$$

d_i in Equation 1 becomes a function of α, β and the known coordinates X_i, Y_i, Z_i and r_i only. Using equation 1 and summing up for all microphones ($i = 1, 2, 3 ...$), solutions are obtained for the two unknowns α and β from the two equations (Equation 2), and the solution for γ from Equation 3.

By solving these equations for the direction cosines, the plane wave through microphone 0 is uniquely determined, considering that the wave must travel in a downward direction. The wavefront may be more conventionally expressed in terms of elevation and azimuth angles, rather than in terms of direction cosines:

$$\phi = \frac{\beta}{\alpha}, \quad e = \pi - \arccos \alpha,$$

where e is the elevation angle of the sound source and ϕ the azimuth angle counted counterclockwise from north to the direction from which the sound arrives. As a further refinement, a spherical wavefront may be fitted to the microphone coordinates X_i, Y_i, Z_i, r_i; this method is described in Reference 18.

The fitting of the wavefront is a lengthy manual computation because the number of microphones is always greater than four and the number of explosions in any firing is greater than 10. The procedure has therefore been programmed on a small digital computer (LGP-30) which can compute the wavefront for one explosion in less than one minute.

Computation of Temperatures and Winds

The method of calculating average temperatures and winds in a horizontal layer between the explosions G_1 and G_2, as illustrated in Figure 2, is described briefly below. It can be extended to the calculation of $n - 1$ temperature and wind values between n explosions.

The soundwave traveling from grenade G_1 to the microphone is displaced by the horizontal wind blowing between the level of grenade G_1 and the ground. This displacement (the vector quantity $\bar{v}_1$) is proportional to the time t_1 that the wave spends in the medium between the grenade and the ground. The same consideration holds for the soundwave from grenade G_2, where the displacement $\bar{v}_2$ is composed of a term $\bar{w}\,\tau$ (the product of $\bar{w}$, the average horizontal-wind vector in the layer between G_2 and G_1, and τ, the time the soundwave spends in this layer) and a term $\bar{v}^*$ (the displacement of the wave from G_2 due to winds below G_1):

$$\bar{v}_2 = \bar{w}\,\tau + \bar{v}^*. \tag{1}$$

The time t_2 elapsing between the explosion of G_2 and the arrival of the sound from G_2 at the ground may be written as

$$t_2 = \tau + t^*, \tag{2}$$

where t^* is the time the soundwave from G_2 spends in the medium below the altitude of G_1.

Generally, the approximation

$$t^* \sin e_2 = t_1 \sin e_1 \tag{3}$$

will hold, where e_1 and e_2 are the average elevation angles along the soundpath from G_1 and G_2, respectively. Because of the proportional relationship between the $\bar{v}$'s and t's,

$$\bar{v}^* \sin e_2 = \bar{v}_1 \sin e_1 \tag{4}$$

The terms t_1 and t_2 are measured quantities, and $\bar{v}_1$ and $\bar{v}_2$ can be calculated from the exact coordinates of the grenade explosions, the temperature and wind field below G_1, and the angles at which the soundwaves arrive at the microphone array. These parameters are measured. Thus, the unknowns $\bar{v}^*$, t^*, τ, and $\bar{w}$ can be calculated from Equations, 1-4, and the average wind in the layer between G_1 and G_2 is determined.

After determining the wind in the layer, Snell's law may be used to compute c, the speed of sound in the layer between G_1 and G_2:

$$c \csc e_1 + \bar{w}_\phi = c_0 \csc e_2, \tag{5}$$

where c_0 is the speed of sound at the microphone array, and $\bar{w}_\phi$ is that component of the wind in the layer which acts within the plane of the southpath trajectory from G_2. At the surface of the earth, the wind is assumed to be zero; e_1 is the average zenith angle of the soundpath from G_2 within the layer between G_1 and G_2, expressed by:

$$\cos e_1 = \frac{H}{c\tau}, \tag{6}$$

where H is the difference in height between G_1 and G_2. Hence, c can be calculated from Equations 5 and 6. The temperature T in the layer is related to c by the equation

$$c = \left(\frac{C_p}{C_v}\frac{RT}{M}\right)^{1/2} \tag{7}$$

where R = universal gas constant, C_p/C_v = ratio of specific heats of the medium between G_1 and G_2, M = mean molecular weight of the medium. These parameters should be available from independent measurements, so that T can be calculated from Equation 7.

An error analysis (Reference 19) indicates that temperature errors generally are less than 1°K, and that the wind error is about 1 m/sec, if the error in determining the coordinates of the grenade explosions is less than 5 meters. The accuracy of determining the temperatures and winds is limited by the random errors inherent in measuring the arrival times of the low-frequency soundwaves at the microphones. For explosions below 75 km, a time error of 2-3 milliseconds is probable, which will result in an uncertainty of the soundwave angle of about 0.1 degrees. The resulting error for temperatures in this case will generally be less than ±3°K; for wind speed and direction, the errors are about ±5 m/sec and ±15°, respectively. For explosions at higher altitudes, sound arrivals at the ground may be so weak that arrival-time errors in some cases may be as large as 5-10 milliseconds. The resulting temperature errors may increase to about ±10°K, while a wind-speed error of about 15 m/sec may be expected. The existence of vertical winds in the layer between G_1 and G_2 is not considered in these calculations, as the speeds of such winds are known to be negligible compared with the velocity of sound.

For grenade explosions at altitudes higher than 50 or 60 km, the calculations must allow for the fact that acoustic energy at these levels propagates as a shockwave rather than a soundwave over a substantial portion of its path (finite-amplitude effect). This correction is small and is described in Reference 20.

The highest altitude from which sound returns can be received, with present explosive charges and existing sound-ranging techniques, is about 90 km. The LGP-30 computer is used to derive temperatures and winds from the coordinates, arrival times, and explosion times. Computationally, the largest effort lies in the determination of $\bar{v}_1$ and $\bar{v}_2$, which is done by ray-tracing the soundwave up to G_1 and G_2, respectively. For error estimates, it is desirable to compute one data point several times under varying input conditions; here a high-speed computer is particularly useful. (A detailed description of this method of analysis is found in Reference 20).

Derivation of Pressures and Densities

The analysis described in the preceding section yields an altitude profile of temperatures and winds as a direct result of the grenade-experiment measurements. The temperature profile—consisting of discrete points, each representing an average value for an altitude layer between grenade explosions—is used to obtain density and pressure profiles, provided the pressure or density is known at a given level at the bottom of the temperature profile. Pressure is calculated by means of the following relation, derived by combining the hydrostatic equation with the ideal gas law:

$$\ln p_i = \ln p_{i-1} + \frac{g(h_i - h_{i-1})}{R(T_i - T_{i-1})} \ln \frac{T_i}{T_{i-1}} , \tag{8}$$

where R is the universal gas constant, g is the gravitational constant which is assumed to vary inversely with the square of the altitude, and p_i the pressure at the altitude h_i at which the temperature T_i has been measured. The levels i can be chosen to represent the midpoint altitudes of each grenade-explosion layer.

The density ρ_i at the level i may then be derived simply from the pressure by using

$$\rho_i = \frac{p_i}{RT_i} . \tag{9}$$

It is more accurate to derive density or pressure from a measured temperature profile, than to derive temperature from a measured density or pressure profile. The reason for this is that, in deriving densities and pressures, an integration must be performed over the temperature profile, which can be done with far more precision than the differentiation involved in the later process.

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