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TECHNICAL MEMORANDUM

X-529

ROCKET EXHAUST EFFECTS ON RADIO FREQUENCY PROPAGATION FROM A SCOUT VEHICLE AND SIGNAL RECOVERY DURING THE INJECTION OF DECOMPOSED HYDROGEN PEROXIDE

By Theo E. Sims and Robert F. Jones

Langley Research Center
Langley Field, Va.

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To ________________________________
NASA LTR DTO Oct. 21, 1969

By authority of S/Jacob E. Smart Date DXC 7/13/70

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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TECHNICAL MEMORANDUM X-529

ROCKET EXHAUST EFFECTS ON RADIO FREQUENCY PROPAGATION FROM A SCOUT VEHICLE AND SIGNAL RECOVERY DURING THE INJECTION OF DECOMPOSED HYDROGEN PEROXIDE

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SUMMARY

Received signal strengths of three VHF telemeter signals (240.2, 244.3, and 259.7 mc/sec) and one C-band radar-beacon signal (5,560 mc/sec) were observed for possible rocket exhaust effects during the ascent phase of Scout ST-1 which was launched from NASA Wallops Station at 7.04 p.m. e.s.t. July 1, 1960. Also a UHF (400 mc/sec) command receiver was monitored for the presence or absence of a signal from a ground-based transmitter.

Significant rocket exhaust effects on the three VHF signals were noted during burning of the second-stage motor from ignition at an altitude of 130,000 feet to the beginning of rocket-motor tail-off or slow burning at an altitude of 258,000 feet. The effects were most severe between the altitudes of 197,000 feet and 258,000 feet. Similar effects were observed during the second-stage burning of Scout ST-2 which was launched from NASA Wallops Station at 10:23 a.m. e.s.t. October 4, 1960.

Only minor exhaust effects on the C-band signal were noted and the signal from the ground-based transmitter was always present in the UHF receiver.

Decomposed hydrogen peroxide, which was injected into the flow field at intermittent intervals by the control jets, caused recovery of the VHF signals. During Scout ST-2 second-stage burning, operation of the hydrogen peroxide control jets also caused VHF signal recovery.

Possible contributing factors to the observed rocket exhaust effects on received signal amplitude and to signal recovery by the injection of decomposed hydrogen peroxide are discussed in this report.

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INTRODUCTION

Rocket exhaust effects on radio frequency propagation from vehicles using liquid fuels were observed as long ago as the German V-2 era. These effects have been under investigation for many years and much has been learned but they are still a problem when uninterrupted telemeter signals are required. Reference 1 is a survey of accomplishments, status, and trends in the field and contains a bibliography of selected references available at the time of its publication. Reference 2 describes some significant ground-based experimental rocket-exhaust work done by the Naval Research Laboratory.

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The most recent flight experiences with rocket exhaust effects on propagation have been with ballistic-missile flights from the Atlantic Missile Range, Cape Canaveral, Florida. The phenomena observed during these flights are described in references 3 and 4. The characteristics of the observed phenomena are usually severe interference with electromagnetic propagation during powered flight with the interference occurring most often between the altitudes of 200,000 feet and 300,000 feet.

Opportunities for studying the rocket-exhaust—radio-frequency interference problem for solid-propellant motors between the altitudes of 200,000 feet and 300,000 feet have been few. The first known occurrence of the interference phenomena for solid-propellant vehicles flown from NASA Wallops Station other than normal stage separation and ignition effects, was observed during the second-stage burning of Scout ST-1 launched at 7:04 p.m. e.s.t. July 1, 1960.

The results of the Scout ST-1 flight are being reported because of widespread interest in ionization effects on electromagnetic propagation and in methods of alleviating these effects. The main purposes of this report are to present the basic data and to describe the observed effects of the rocket exhaust and of the hydrogen peroxide control jets on the telemeter signal strength. A brief review of possible causes of the observed phenomena is included; however, no effort has been made to provide a thorough scientific analysis of the effects.

ROCKET MODEL AND FLIGHT CONDITIONS

Rocket Model

The Scout vehicle configuration is shown in figure 1. The station numbers in the figure locate important parts of the vehicle in inches from a reference point 4.8 inches forward of the nose tip. The vehicle consists of four powered stages and the payload. All the motors are solid-propellant rockets but important parameters such as fuel burning rate, combustion products, and rocket chamber pressure differ from motor to motor. The rocket motor most important to this presentation is the second stage. The significant characteristics of this motor are given in table I. The list of combustion products was furnished by the rocket manufacturer. The ratio of specific heats was estimated. All other values were measured.

The vehicle is guided along the prescribed trajectory by a guidance and control system. During first-stage burning, guidance is accomplished by controlling the cant of the fin tips. During second-stage and third-stage burning, guidance is accomplished by roll, pitch, and yaw hydrogen peroxide control jets. The fourth stage is spin stabilized. The controls most important to this report are the second-stage hydrogen peroxide jets. The location of these jets is shown in figure 2. There are eight jets: Two pitch, two yaw, and four roll. The important characteristics of these jets are listed in table II. The mass-flow rates, chamber pressure, and adiabatic decomposition temperature are measured values. The oxygen content of the reaction products is a calculated value.

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Flight Conditions

The three curves in figure 3 describe the trajectory flown by Scout ST-1 during second-stage burning. Altitude, ground range, and velocity are plotted with respect to time. Data for these curves were obtained from the radar plot of the trajectory flown. The region of interest is from ignition to burnout of second stage.

National Bureau of Standards ionospheric sounding stations at Boulder, Colorado, and Ft. Belvoir, Virginia, reported that the ionosphere was normal at the time of launch of Scout ST-1 with no detectable unusual activity in progress.

INSTRUMENTATION AND MEASUREMENTS

Instrumentation

During second-stage burning there were two standard IRIG (Inter-Range Instrumentation Group) FM/FM telemeters, one standard NASA FM/AM telemeter, one UHF command receiver, and one C-band radar beacon in operation. Antenna locations are shown in figure 2. As is shown in this figure, two of the VHF signals are diplexed to one antenna. Radiation patterns for the VHF and C-band antennas are given in figures 4, 5, and 6. Signal·frequencies, power levels, and antenna types are given in table III.

Ground-support instrumentation included VHF telemetry receiving stations, a UHF command transmitter, and a C-band radar at NASA Wallops Station, Wallops Island, and a VHF telemetry receiving station at the Langley Research Center, Langley Field. The VHF telemetry receiving stations at Wallops Island used helix and yagi antennas while the station at Langley Field used a yagi antenna.

Figure 7 is a rough map which shows the general orientation of Wallops Island, Langley Field, and the vehicle during second-stage burning. Figure 8 shows the orientation of vehicle antennas and hydrogen peroxide control jets with respect to look angles from Wallops Island and Langley Field.

Measurements

The basic measurements obtained in this investigation were (1) received signal strengths of the three VHF signals and the C-band signal at the Wallops Island stations, (2) received signal strength of the 244.3 mc/sec VHF signal at Langley Field, (3) presence or absence of a signal in the vehicle command receiver from a transmitter located at Wallops Island, (4) rocket-motor headcap pressure, (5) on and off periods of yaw, pitch, and roll hydrogen peroxide control jets, and (6) vehicle attitude changes in yaw, pitch, and roll. Items (1) and (2) were obtained by direct ground recordings while data for items (3) to (6) were telemetered from the vehicle. The VHF signal strengths and telemetered data received at Wallops Island receiving stations were recorded on the same magnetic tape to yield the composite signal-strength—telemeter-data record shown in figure 9. This figure permits accurate time correlation of important events occurring during the vehicle flight.

RESULTS

During second-stage burning of Scout ST-1 no instrumentation or control-system malfunctions occurred and the vehicle and control-system performance was such that for altitudes from 197,000 feet to 258,000 feet the vehicle attitude varied less than 1° in yaw, 0.4° in pitch, and 0.6° in roll. In all probability, therefore, the observed phenomena were due to neither equipment malfunction nor vehicle-attitude change.

Rocket Exhaust Effects

The rocket exhaust effects on the VHF signals received at Wallops Island are evident in figure 9. Upon second-stage ignition at an altitude of approximately 130,000 feet, indicated by a sudden rise in headcap pressure, a rapid drop in the received signal strength with gradual return toward normal was observed for all frequencies. This type of signal loss at stage separation and ignition is not unusual and is generally referred to as staging effects (ref. 3). It is believed to be caused by such things as (1) a change in radiated power because of the decrease in vehicle length when a stage separates, (2) a change in radiation patterns because of reflections from the separating stage, (3) antenna detuning or breakdown occurring when the separated stage deflects the exhaust of the next stage into the vicinity of the antennas, and (4) attenuation or reflection caused by the newly ignited rocket.

At an altitude of 197,000 feet more severe effects on all VHF signals began simultaneously. As shown in figure 9, signals received at Wallops Island directly behind the vehicle decreased in amplitude a maximum of 20 decibels relative to the amplitudes before the severe effects started. At the same time the signal received at Langley Field increased a maximum of 5 decibels relative to the amplitude before the severe effects started. Sections of a Wallops Island record and the Langley Field record correlated in time are compared in figure 10.

The line-of-sight transmission paths from the vehicle antennas to the receiving stations with respect to the rocket exhaust are shown in figure 11.* At an altitude of 200,000 feet the exhaust diameter was estimated to be 80 feet and the jet inclination angle was approximately 90°. These values were estimated by using table I and reference 5. The vehicle antennas were located approximately 31 feet and 37 feet forward of the second-stage nozzle. (See fig. 2.) The signal monitored at Langley Field was from the antenna which was approximately 37 feet forward of the nozzle. The look angles were 4° from Wallops Island and 54° from Langley Field. (See fig. 8.)

At an altitude of 258,000 feet the three VHF signals recovered and no further exhaust effects were observed. This signal recovery occurred just after the beginning of rocket motor tail-off, indicated in figure 9 by a gradual decrease in headcap pressure.

The rocket exhaust effects on the C-band signal are shown in figure 12. Typical signal dropout with gradual return to normal occurred at second-stage ignition. For altitudes from 197,000 feet to 258,000 feet where severe effects on the VHF signals occurred, only minor noise was observed on the C-band signal-strength record.

The UHF command receiver which was being monitored for the presence or absence of a signal from a ground-based transmitter did not lose signal because of flame effects except at rocket-motor ignition. This was as expected because the power margin in the UHF system was sufficient to permit large attenuations without total signal loss. The automatic gain control voltage of the airborne receiver was not monitored.

Only stage-separation effects were observed during the burning of the third and fourth stages.

Rocket exhaust effects on radio frequency propagation similar to those described for Scout ST-1 also occurred during second-stage burning of Scout ST-2. Scout ST-2 was launched from NASA Wallops Station at 10:23 a.m. e.s.t October 4, 1960.

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Signal Recovery During Rocket Exhaust Effects

During the period of rocket exhaust effects on the VHF signals, intermittent signal recovery was observed. This signal recovery is shown in the received-signal-strength record in figure 9. It is first observed as slight humps in the record during the staging effects. During the subsequent period of severe rocket exhaust effects the intermittent recovery is more apparent, with complete recovery from the 20-decibel loss caused by the rocket exhaust. During the same intermittent recovery periods the signal received at Langley Field, which had increased 5 decibels because of the rocket exhaust effects, returned to normal as shown in figure 10.

Each period of intermittent VHF signal recovery began exactly at the time of operation of either a pitch-down or a yaw right hydrogen peroxide control jet. The period of operation is indicated in figure 9. The recovery period was longer when there was a time overlap in the operation of a pitch and yaw jet. The pitch-up and yaw left jets did not operate during the period of rocket exhaust effects. The roll jets, which were much smaller than the pitch and yaw jets (see table II), caused some improvement of the signal but did not cause complete recovery.

Similar signal recovery on injection of decomposed hydrogen peroxide into the flow field occurred during the second-stage burning of Scout ST-2.

DISCUSSION

Rocket Exhaust Effects

Rocket exhaust effects on radio frequency propagation are generally attributed to free electrons (refs. 1 to 4). In sufficient concentrations these electrons can absorb and reflect telemeter signals and enhance antenna breakdown. The required concentration has been theoretically determined by many sources. See references 6 and 7 as examples. For the high-altitude case under consideration and the VHF frequencies used, the electron concentration required is estimated to be 10^9 cm^{-3} or greater. This electron-concentration requirement is analogous to the critical concentrations associated with radio propagation in the ionosphere. The reflective and absorptive properties of the ionosphere exhibit a sharp dependence on frequency. Signals below a critical or plasma frequency are reflected or absorbed while signals above the plasma frequency are essentially unaffected. The plasma-frequency concept is a function of the ambient electron concentration and is described in reference 7.

For the Scout vehicle the problem is to specify the source of electrons. It is possible that several factors contributed to producing the conditions necessary to cause the exhaust effects that were observed. A list and brief discussion of these factors follow:

1. Afterburning - One source of free electrons was probably the chemical reactions (refs. 8, 9, and 10) occurring in the combustion zone or near the rocket nozzle exit. At high altitudes the reduced atmospheric pressure causes rapid expansion of the exhaust products, which may hinder electron recombination processes. The result would be higher electron concentrations away from the rocket nozzle than at sea level. A more important source of electrons however may be the chemical reactions resulting from afterburning. (The electron concentration in a burning flame is commonly much higher than the equilibrium concentration in the combustion products.) Most rocket motors are fuel rich and some of this excess fuel escapes into the exhaust unburned. The Scout second stage was no exception. Several of the products of combustion listed in table I (in particular, H_2 and CO) are combustible and these needed only to come in contact with an oxidizer to cause afterburning. The most logical place for this afterburning to occur was at the exhaust surface where air from the flow field is readily available. The result of such surface afterburning would be a region at the interface of the rocket exhaust and the flow field with a high electron concentration.

2. Electrons from the ionosphere - Another source of free electrons is the ionosphere. The altitude of interest is in the ionosphere D region where the free-electron concentration is approximately 10^3 cm^{-3}. This is a rather low value when considered alone but by interacting with the flow field and rocket exhaust, it is possible that these electrons from the ionosphere may have enhanced reactions in the high-temperature regions about the vehicle and flame. Perhaps some significance can be attached to the fact that the most severe flame effects for Scout ST-1

started at an altitude of 197,000 feet which is the approximate beginning of the ionosphere D region.

3. Rocket-exhaust expansion - Once electrons are generated in sufficient quantities to affect telemeter signals, the size and shape of the exhaust becomes important. In the case of the Scout vehicle, at an altitude of 200,000 feet, the rocket-exhaust diameter of approximately 80 feet was large compared with the vehicle diameter and antenna size and probably acted essentially as a ground plane.

4. Separated flow - For some aerodynamic considerations the rocket exhaust possibly becomes an integral part of the vehicle; therefore, the size and shape of the rocket exhaust could influence the flow characteristics about the vehicle. At high altitudes where the exhaust is large it may even cause a region of separated flow on the vehicle. The temperature of the separated-flow region may approach the stagnation-point temperature. Also the reattachment of the boundary layer to the rocket exhaust may cause a high-temperature region at the exhaust surface. During the period of interest the Scout vehicle was accelerating from 6,000 ft/sec to 8,000 ft/sec. The resultant temperatures in the separated-flow region and the boundary-reattachment area were too low to provide an electron concentration of 10^9 cm^{-3} when considered alone; however, it is possible that they did contribute to the overall ionization levels, especially at the interface of the rocket exhaust and flow field.

Antenna breakdown probably was not a factor in the Scout ST-1 signal-strength variations because (1) the effects on all signals were simultaneous regardless of power levels, (2) the slow rate of signal decay did not portray the sharp discontinuity usually associated with antenna breakdown (ref. 3), and (3) the signal increased at Langley Field.

As is shown in figure 9 the recovery of the VHF signals at an altitude of 258,000 feet with no further exhaust effects noted corresponded with the beginning of rocket-motor tail-off. The headcap pressure had dropped approximately 15 percent. This in itself may not be important. What may be important, however, is the fact that at tail-off the motor protective lining starts to burn along with the remaining fuel and this (the lining has a high carbon content) may have altered the products of combustion and thus the ionization intensity in the exhaust.

Signal Recovery During Rocket Exhaust Effects

Instrument malfunction and vehicle attitude change (fig. 13) have been eliminated as causes of signal recovery when the hydrogen peroxide control jets operated. A list and brief discussion of the possible reasons for this signal recovery follow:

1. Cooling of the interface of the exhaust and flow field - The decomposed products of hydrogen peroxide were injected into the flow region near the rocket nozzle exit. The rapid expansion of these products may have significantly cooled the interface of the exhaust and flow field and any separated-flow region that existed. It is difficult to visualize how these products could mix with the exhaust as a whole or greatly affect its size and shape; therefore, surface-region effects are indicated.

2. Removal of free electrons by attachment - The products of decomposed hydrogen peroxide are 60 percent steam and 40 percent oxygen (table II). Oxygen is two electrons short of completion in its outer shell; therefore, it has an affinity for free electrons (refs. 11 and 12) and the excess oxygen may have significantly decreased the electron concentration by removing electrons from the flow-field—rocket-exhaust interface. The separated-flow region and rocket-exhaust—flow-field interface would provide a good mixing zone for reducing surface-region effects.

CONCLUDING REMARKS

Rocket exhaust effects on VHF propagation from Scout ST-1, which used solid-propellant rocket motors, were observed during second-stage burning at altitudes from 130,000 feet to 258,000 feet. Similar effects on the VHF signals from Scout ST-2 were also noted. These effects, which were observed as reduction of signal strength at receiving stations behind the vehicle and enhancement of signal strength at a receiving station to the side of the vehicle, were probably caused by free electrons in the region of the exhaust—flow-field interface. Possible contributing factors were (1) afterburning, (2) ionospheric enhancement, (3) rocket-exhaust expansion, and (4) separated flow.

Injection of decomposed hydrogen peroxide into the flow field removed the rocket exhaust effects for Scouts ST-1 and ST-2. Possible reasons were (1) removal of free electrons by recombination in cooling the exhaust—flow-field interface and (2) removal of free electrons by attachment to the excess oxygen.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., January 4, 1961.

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TABLE I

PERTINENT DATA ON SCOUT SECOND-STAGE ROCKET MOTOR

[All values listed are approximate]

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Total fuel weight, lb	7,300
Fuel burning rate:	
Percent in first 27 seconds	89 (240 lb/sec)
Percent in next 11 seconds	11 (tail-off)
Products of combustion (inside combustion chamber):	
Product	Mole fraction
Al_2O_3	0.06615
CO	0.24655
H_2O	0.12286
H_2	0.30532
S	0.00364
N_2	0.07592
HCl	0.15180
CO_2	0.02765
H	0.000076
OH	0.000025
Chamber pressure, lb/sq in. abs	520
Exit pressure, lb/sq in. abs	4
Chamber temperature, °F	5,225
Exit temperature, °F	2,580
Ratio of specific heats	1.2
Throat diameter, in.	9.69
Exit diameter, in.	38.5
Divergence angle of nozzle, deg	20.66
Exit density, lb/cu ft	0.00328
Density just outside exit, lb/cu ft	0.001 to 0.002
Exit Mach number	3.41

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TABLE II

HYDROGEN PEROXIDE JET CHARACTERISTICS

[All values listed are approximate]

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Number of jets (2 yaw, 2 pitch, and 4 roll)	8
Jet location	Around second-stage nozzle
Mass-flow rate, lb/sec:	
Pitch and yaw jets	3.5
Roll jets	0.143
Chamber pressure, lb/sq in. abs	300 to 400
Decomposition process: Hydrogen peroxide (90 percent pure) is passed through a silver screen catalyst which converts it to oxygen (40 percent) and steam (60 percent)	
Adiabatic decomposition temperature, °F	1,364

TABLE III

SIGNAL FREQUENCIES, TRANSMITTER POWERS, AND ANTENNA TYPES

Frequency, mc	Frequency band	Power	Antenna type
240.2	VHF	8 watts	Dipole spikes
244.3	VHF	1.5 watts	Dipole spikes
259.7	VHF	12 watts	Dipole spikes
400	UHF	Receiver	Dipole bowtie
5,560	C	400 watts peak	Stub with reflector

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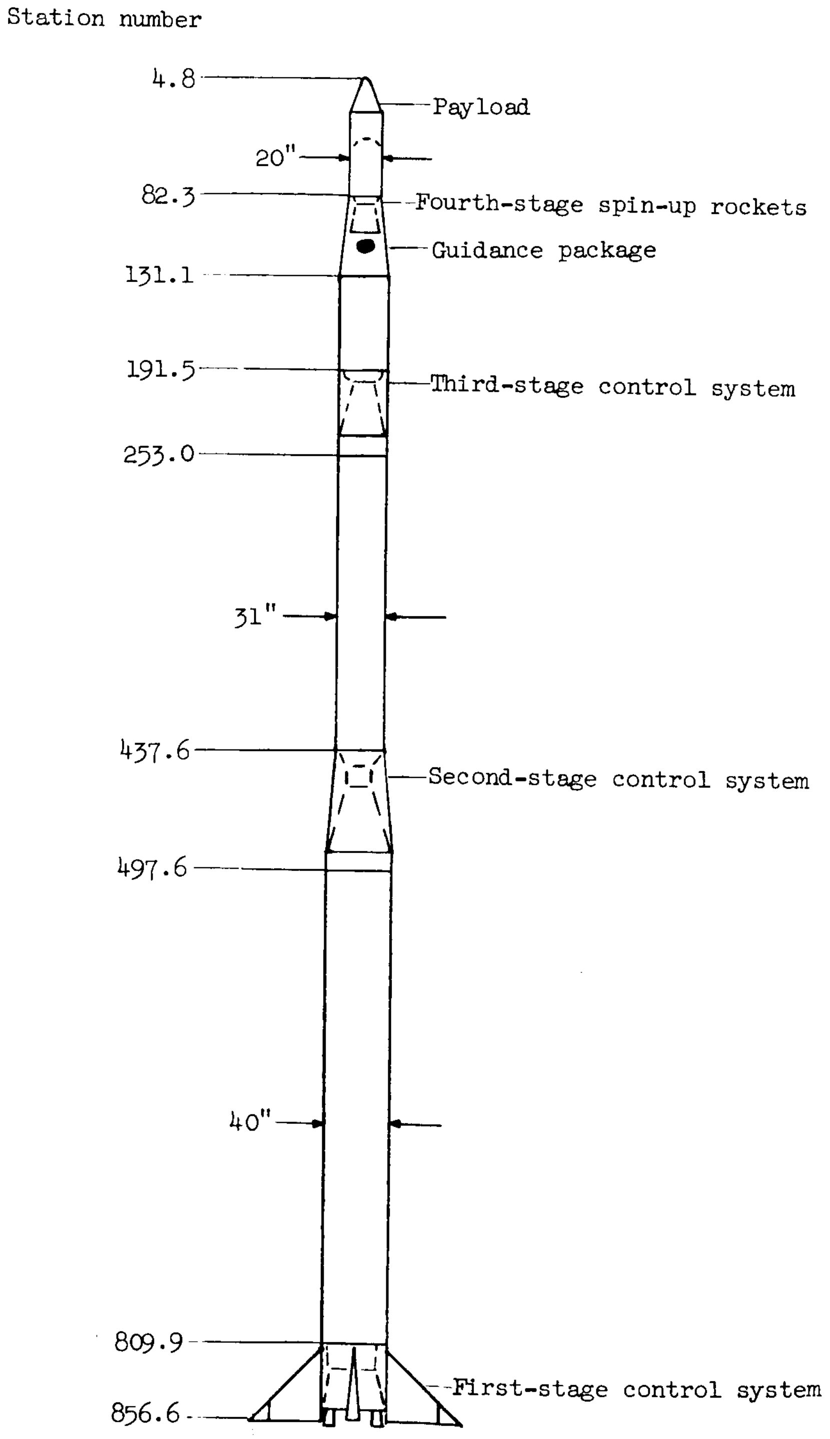

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Figure 1.- Vehicle configuration. Scout ST-1.

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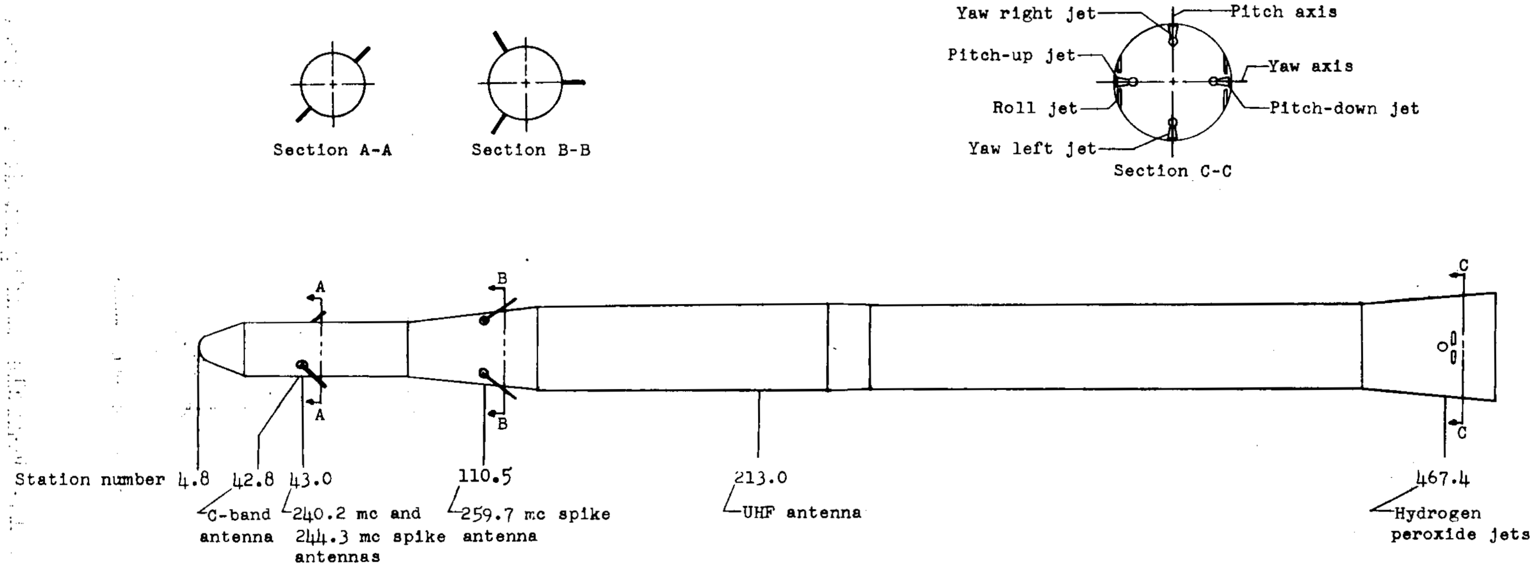

Figure 2.- Location of hydrogen peroxide control jets and antennas. Scout ST-1.

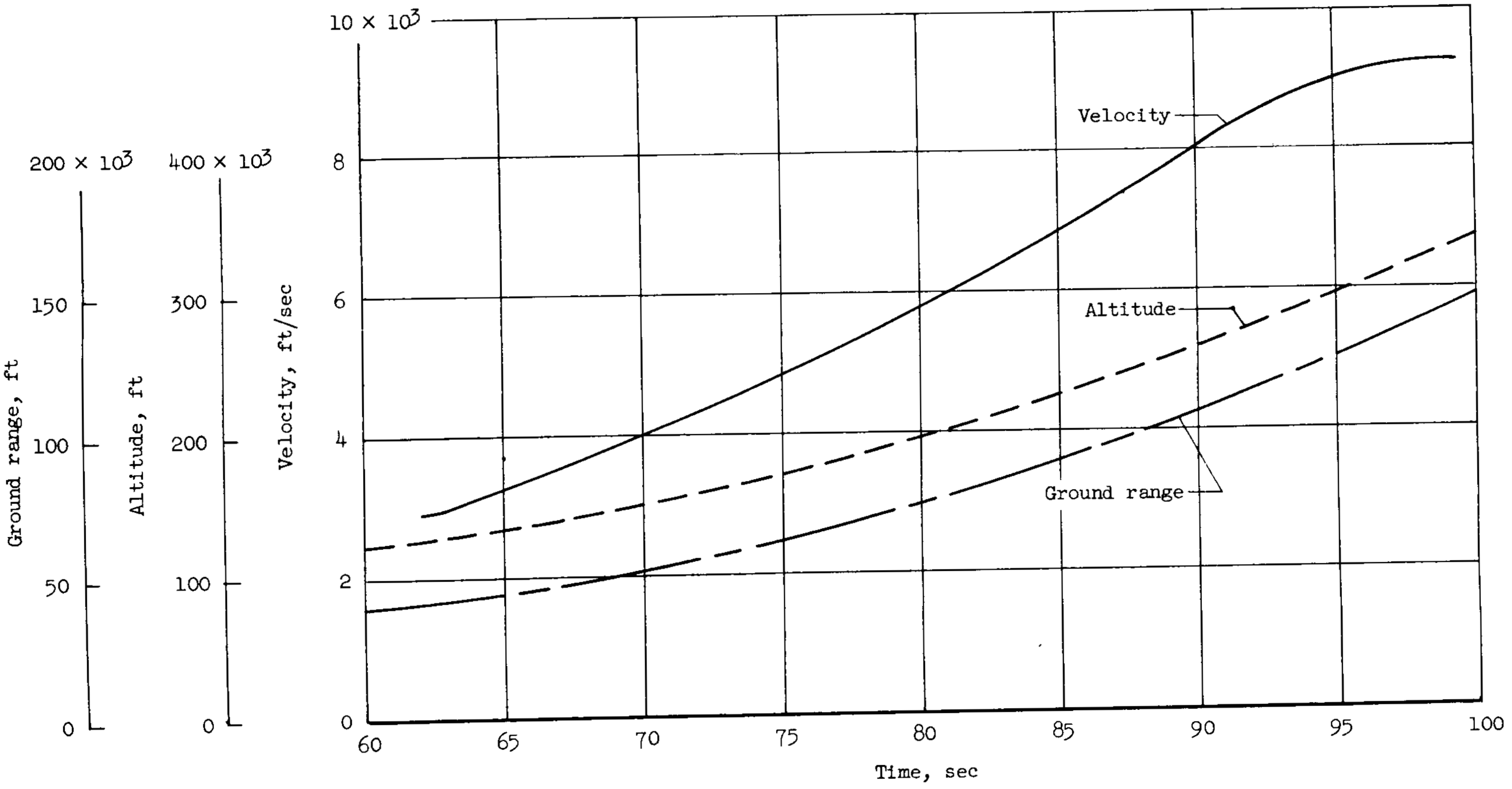

Figure 3.- Trajectory during second-stage burning. Scout ST-1.

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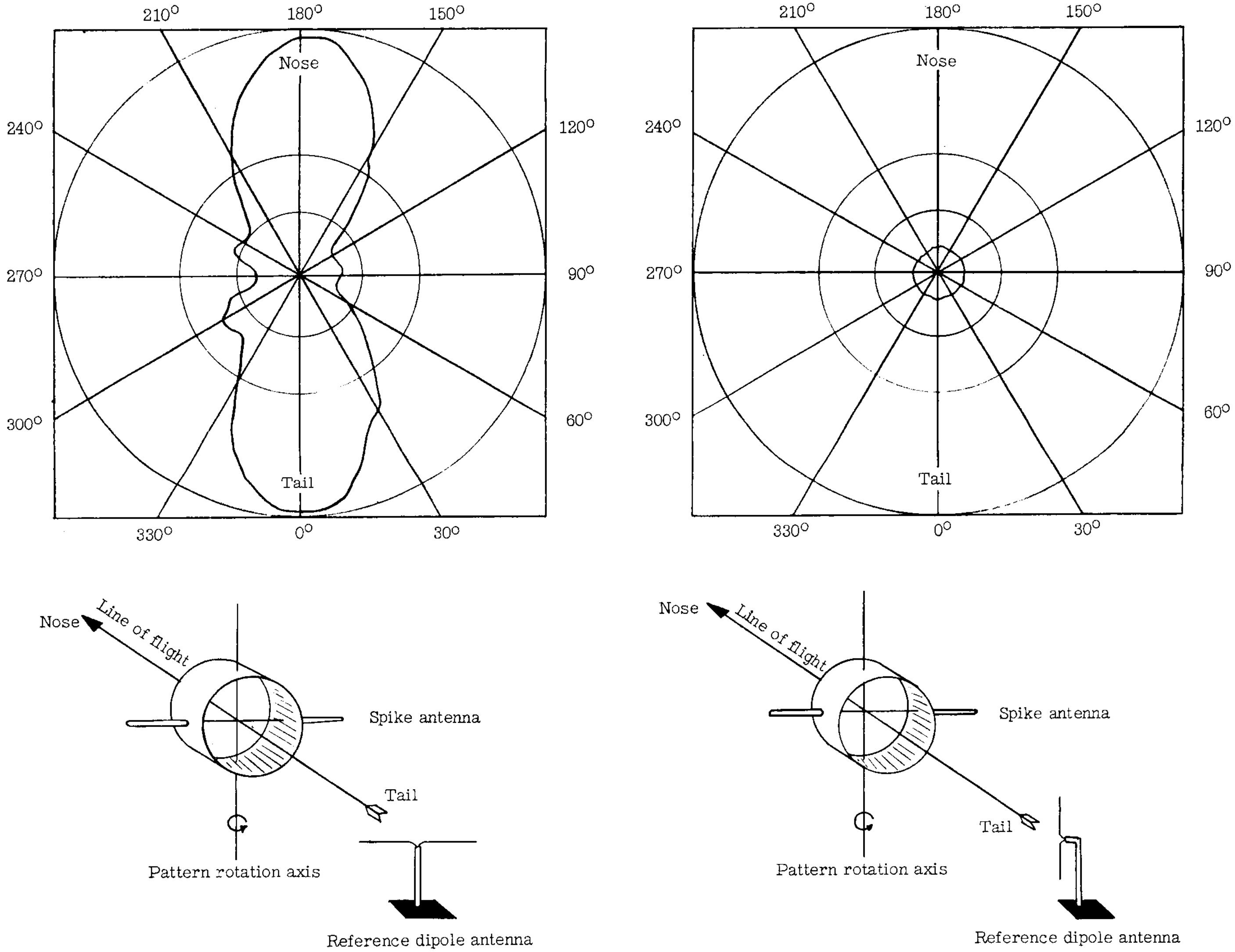

Figure 4.- Radiation patterns for 240.2 mc and 244.3 mc antennas located at station 43. Scout ST-1.

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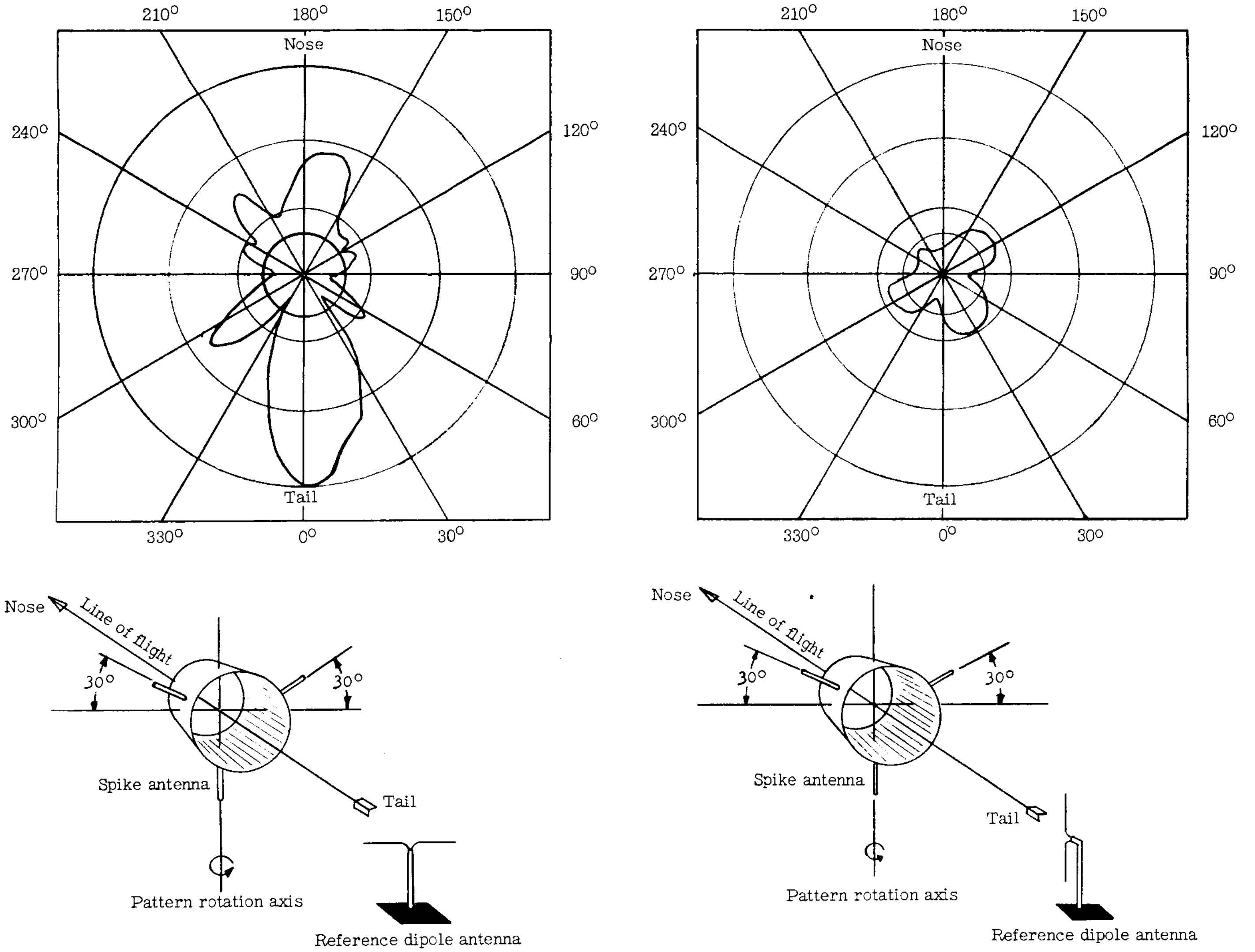

Figure 5.- Radiation patterns for 259.7 mc antenna located at station 110.5. Scout ST-1.

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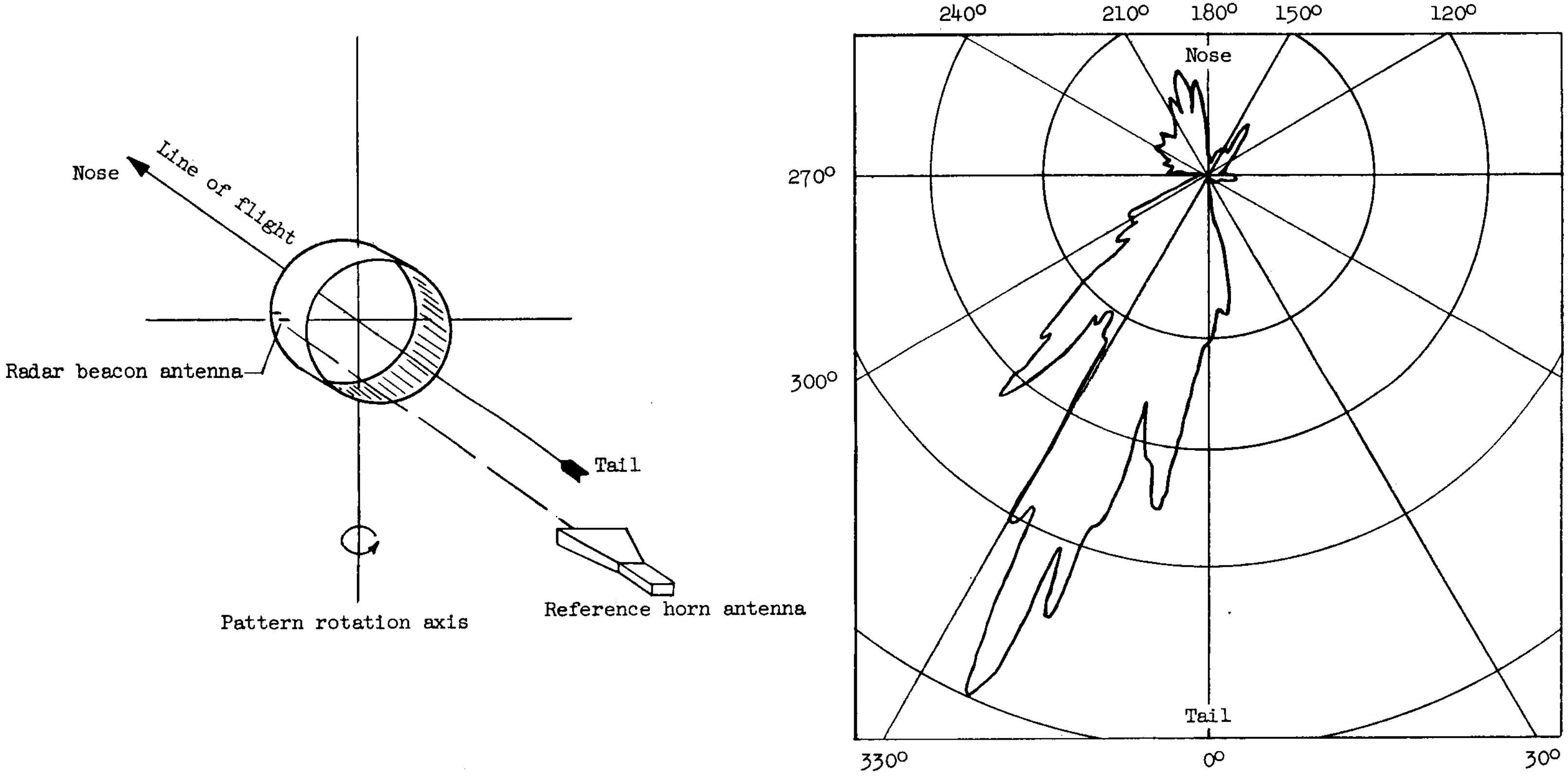

Figure 6.- Radiation pattern for C-band antenna located at station 42.8. Scout ST-1.

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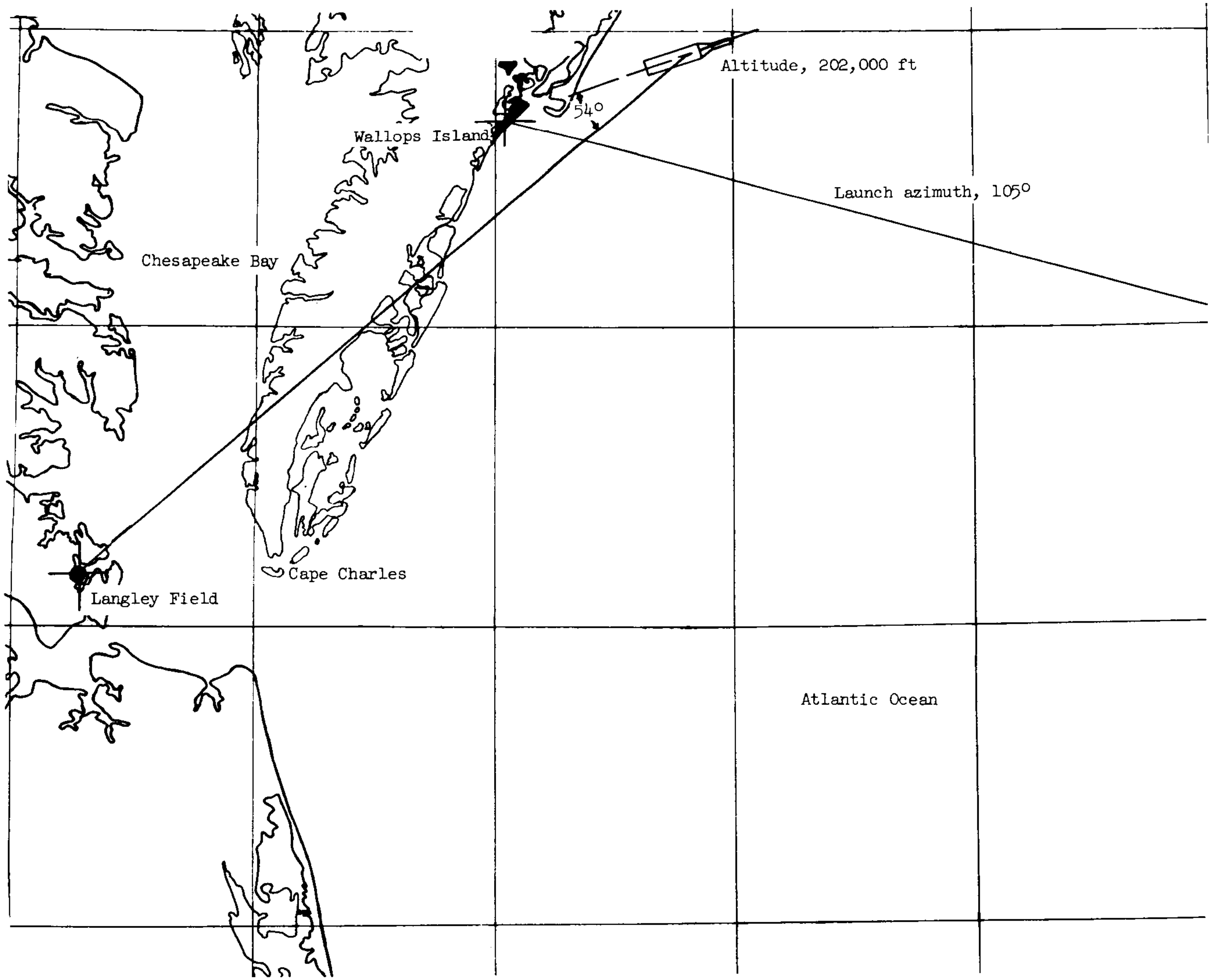

Figure 7.- Vehicle orientation with respect to receiving-station locations during second-stage burning. Scout ST-1.

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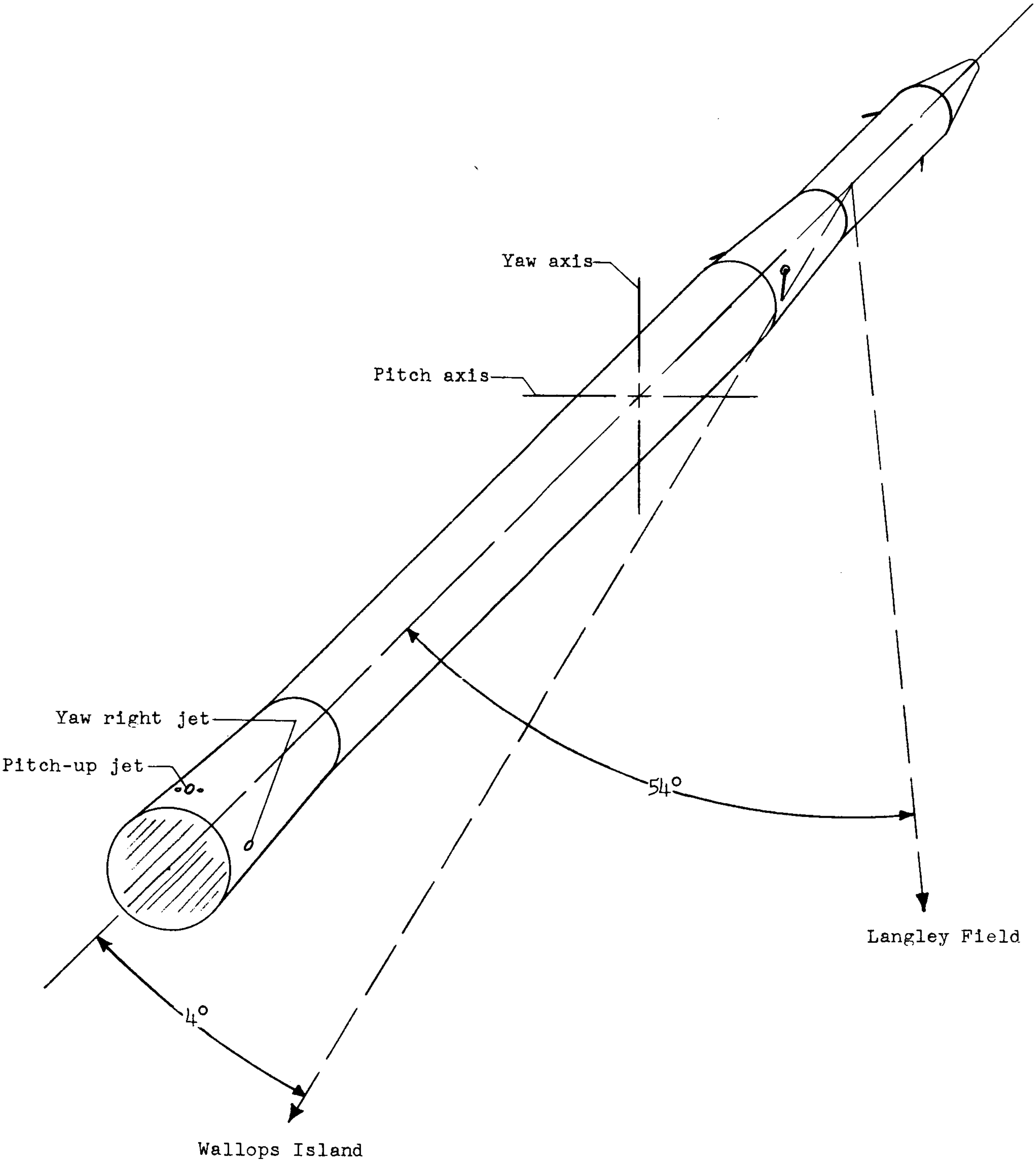

Figure 8.- Antenna and control-jet orientation with respect to receiving stations. Scout ST-1.

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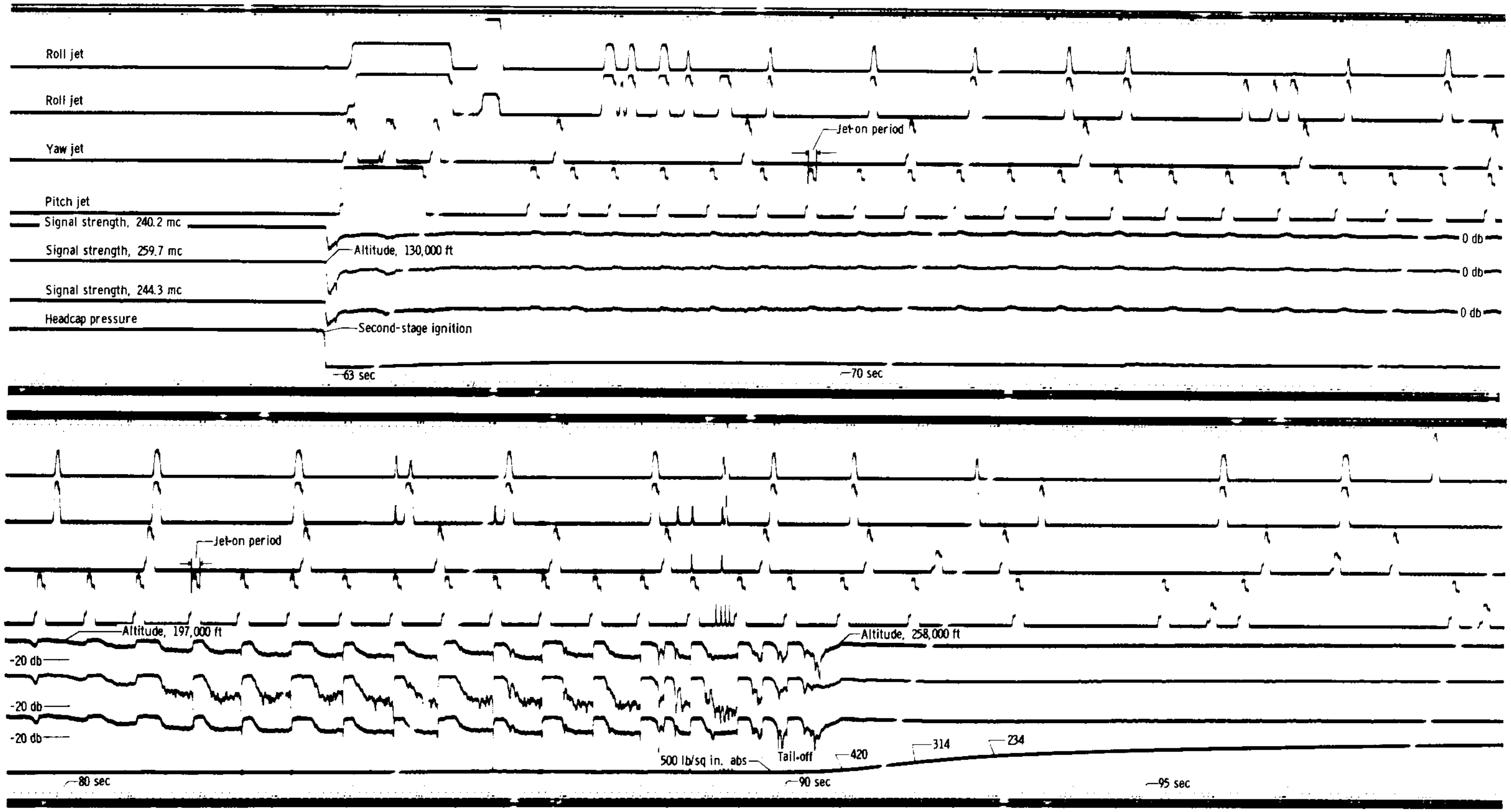

Figure 9.- Wallops Island record showing received signal strength and telemeter data during second-stage burning. Scout ST-1.

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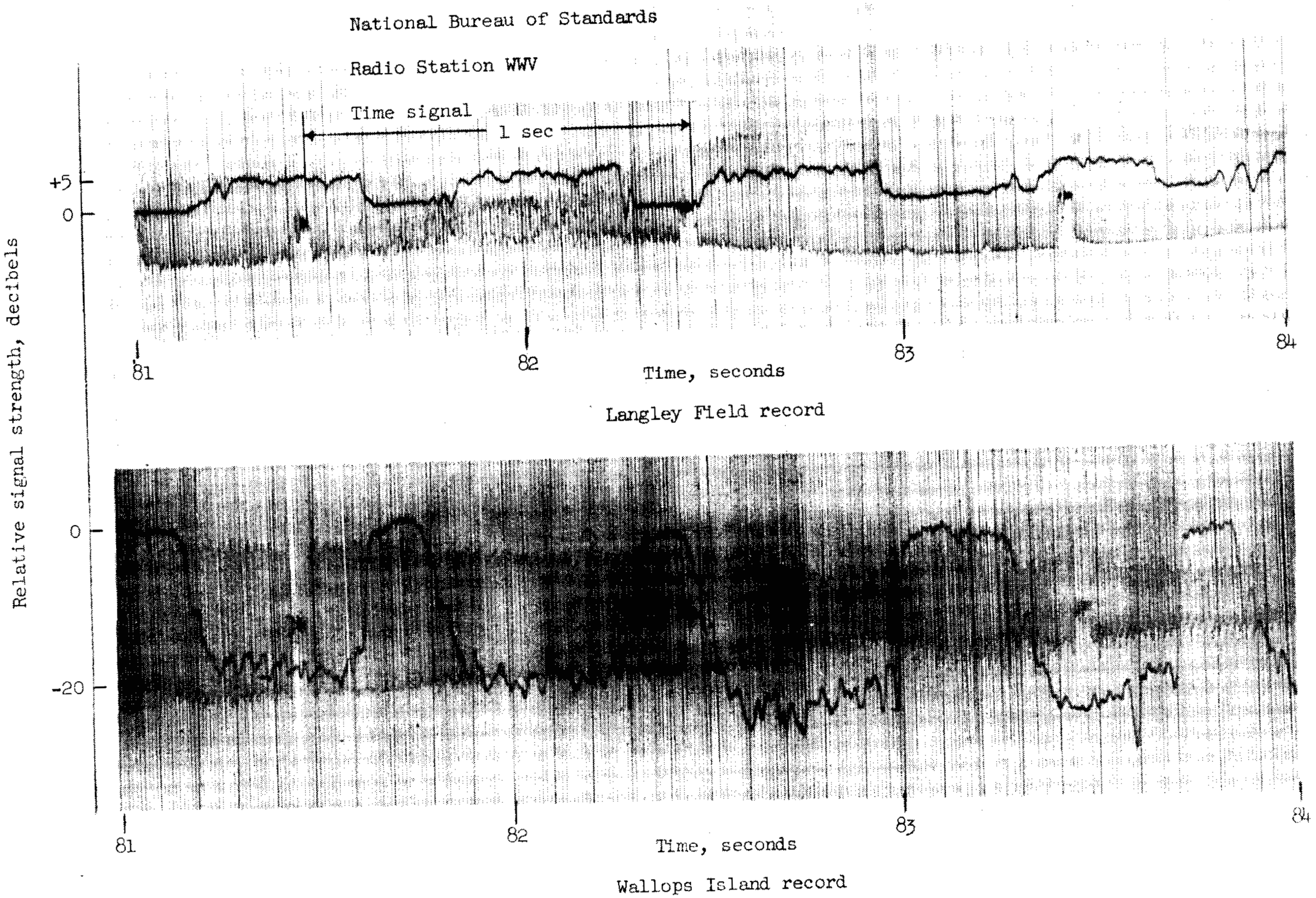

Figure 10.- Comparison of received-signal-strength records from Wallops Island and Langley Field. Scout ST-1.

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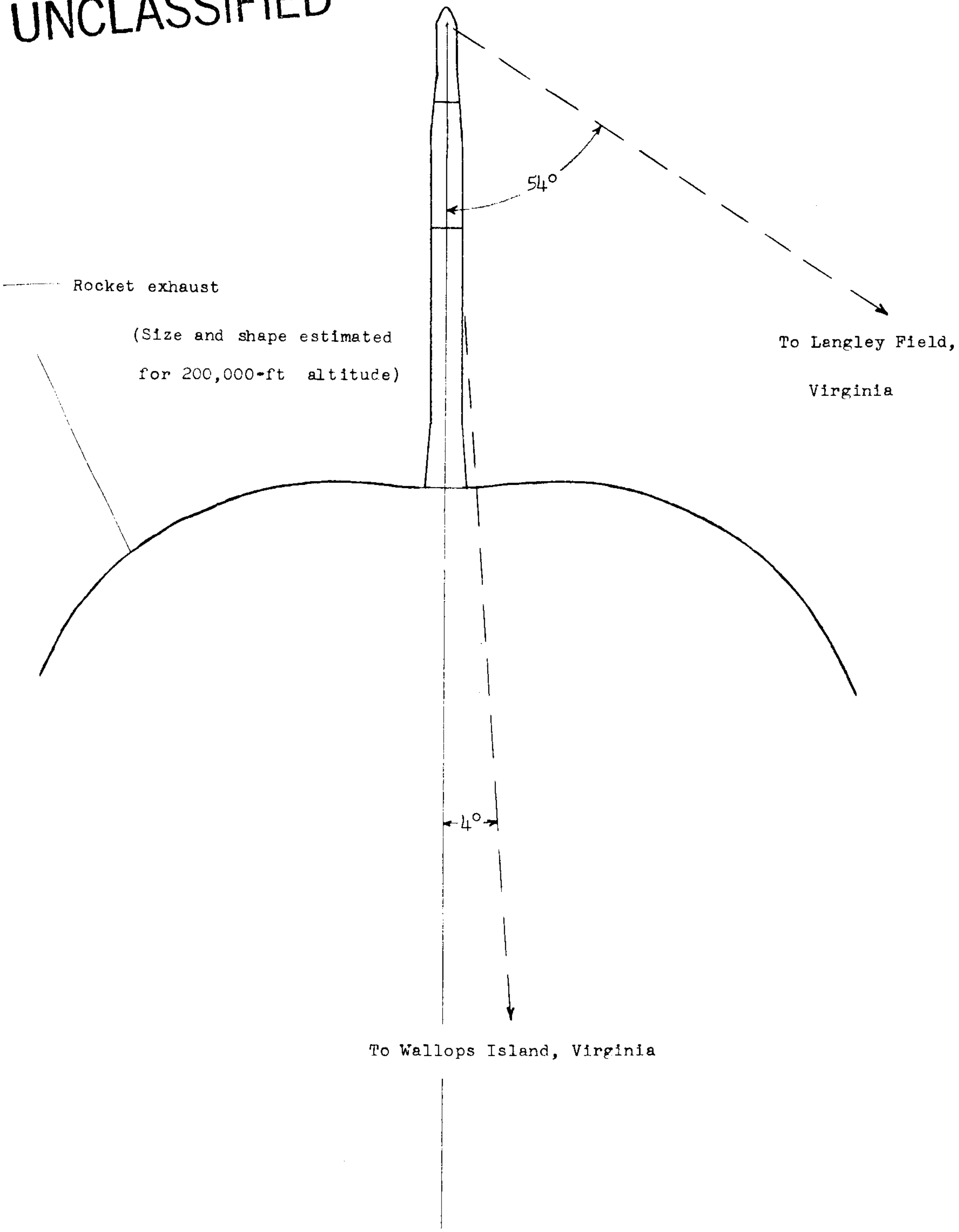

Figure 11.- Rocket exhaust at altitude of 200,000 feet with respect to line-of-sight transmission paths from vehicle antennas to receiving stations. Scout ST-1.

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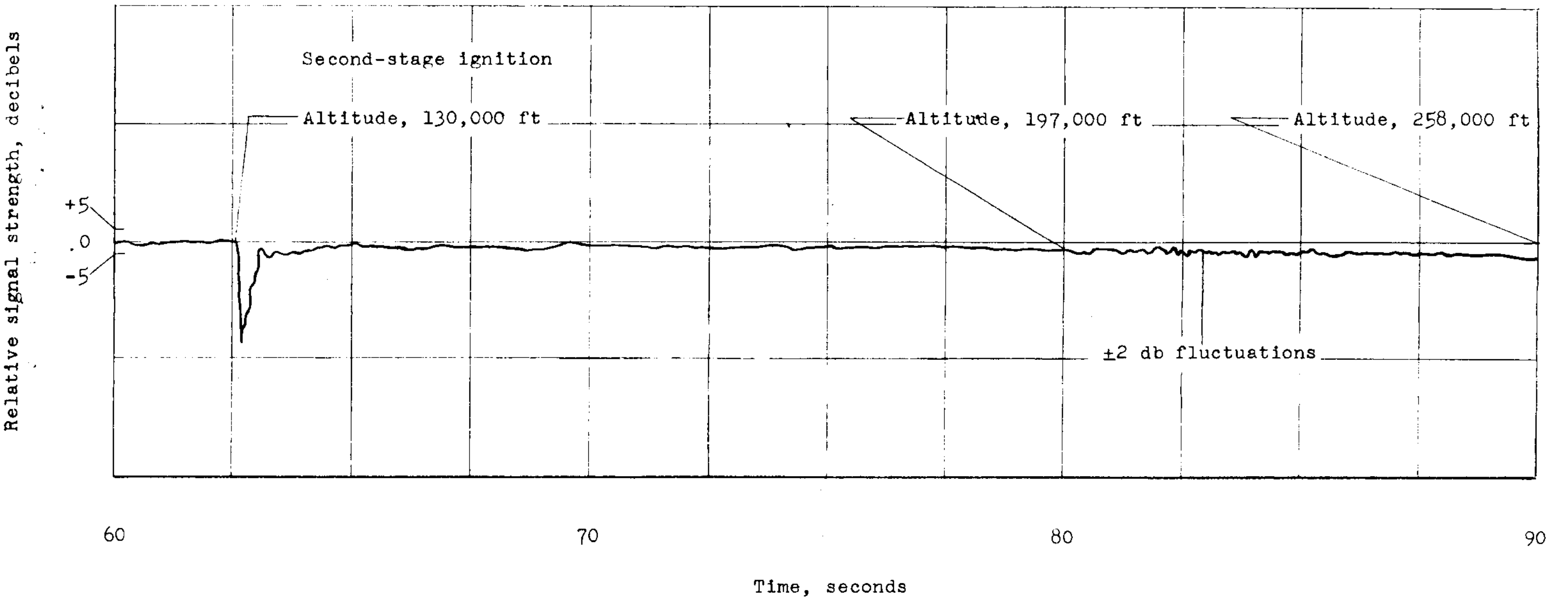

Figure 12.- Wallops Island record showing received signal strength of the C-band signal. Scout ST-1.

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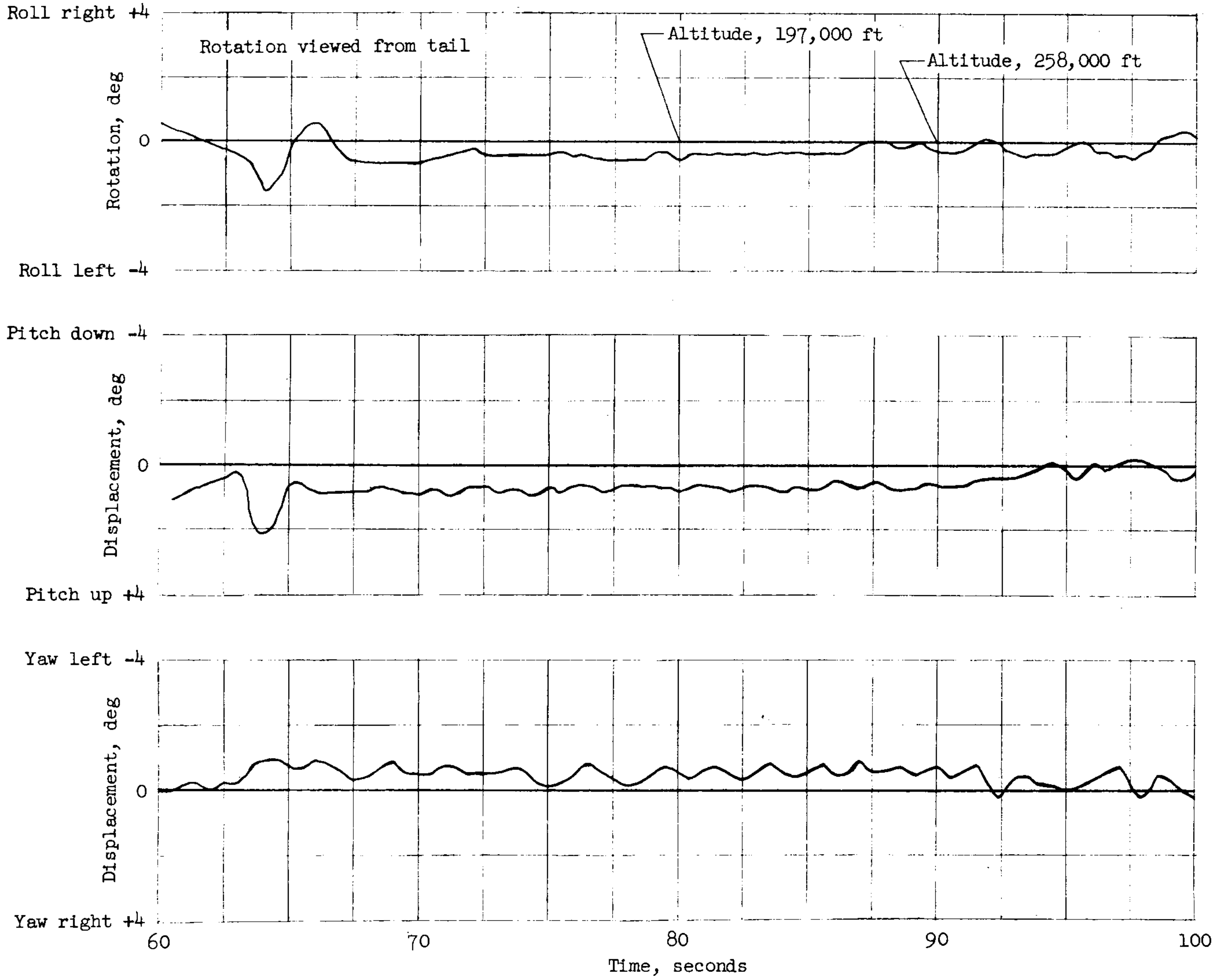

Figure 13.- Vehicle attitude changes in roll, pitch, and yaw. Scout ST-1.