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A SMALL MULTI-PURPOSE ROCKET PAYLOAD FOR IONOSPHERIC STUDIES

by S. J. Bauer and J. E. Jackson

Goddard Space Flight Center
Greenbelt, Maryland

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JUNE 1964

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A SMALL MULTI-PURPOSE ROCKET PAYLOAD FOR IONOSPHERIC STUDIES*

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SUMMARY

A miniaturized version of the two-frequency CW propagation experiment has been developed for ionospheric measurements using small (15 cm diameter) sounding rockets. The choice of relatively high frequencies (24.5 and 73.6 Mc) for the propagation experiment permitted the use of a very simple configuration for the rocket antenna. The signals received on the ground at the two frequencies were about four microvolts/meter for a slant range of about 180 km. About half of the payload space for a Nike-Cajun rocket is occupied by the CW propagation experiment, leaving the remaining space available for one or two secondary experiments. Two telemetry channels for these experiments are provided by modulation of the 73.6 Mc signal. A very high degree of frequency stability was provided in the two-frequency transmitter to permit Doppler radial velocity measurements at 73.6 Mc. A stability of 1 part in 10^8 has been achieved in ballistic flight, and about 1 part in 10^6 during the propulsion phase. If ranging errors during the propulsion phase can be overcome, the complete rocket trajectory can be calculated with an accuracy of 1% of the maximum altitude from the Doppler data at a single receiving site.

The payload has been successfully flown on two Nike-Apache rockets, launched from Wallops Island, Virginia, late in 1962. The propagation experiment yielded electron density profiles from 85 to 160 km, and the secondary experiment, a Langmuir probe, provided in-situ measurements of ionospheric parameters. The paper discusses the payload design, the flight performance and the results of the ionospheric experiment. A new method for tracking using the CW propagation experiment is also outlined. The self-sufficient nature and relatively low cost of the payload should make it well suited for general use by the international scientific community.

INTRODUCTION

In the altitude region below about 250 km, a region inaccessible to satellites, sounding rockets represent one of the most important tools for basic geophysical studies. Although this altitude region is covered to some extent by ground-based techniques (e.g., ionosondes), there are still a number of problems which can best be solved by direct measurements. Furthermore, it is

*Presented to the COSPAR Working Group Number 2 for the IQSY at the 4th International COSPAR Meeting, Warsaw, Poland, June 3-12, 1963.

necessary for a detailed understanding of the physics of the ionosphere to measure *simultaneously* parameters affecting the structure of the ionosphere. Among the problems amenable to a solution by small sounding rockets are measurements of sporadic E, the equatorial electrojet, the extent of a possible valley between the E and F layers, the absorption of X and UV radiation responsible for the formation of the lower ionosphere, as well as the composition of neutral and ionic species. Typical problems presented by this region as well as the measurement techniques used are summarized in Figure 1.

For this reason, we have developed a small multiple purpose payload which contains one experiment whose information is basic to all studies of the ionosphere, i.e., the electron density. This quantity is measured by the well established CW propagation technique using the dispersive Doppler effect at two harmonically related frequencies. In addition, the higher frequency is also used for the telemetry of two additional experiments, as well as to obtain trajectory information from the Doppler effect.

The two-frequency CW propagation experiment, first introduced by Seddon (Reference 1) has been successfully used in the past in small sounding rockets before and during the International Geophysical Year (References 2 and 3) as well as in high altitude rockets in the 1960's (References 4 and 5). In these experiments relatively low frequencies had been used with harmonic ratios of about 6; the higher frequency usually being 73.6 Mc. Use of low frequencies, however, requires more complicated antenna systems (e.g., erectable dipoles) to assure sufficient efficiency of radiation.

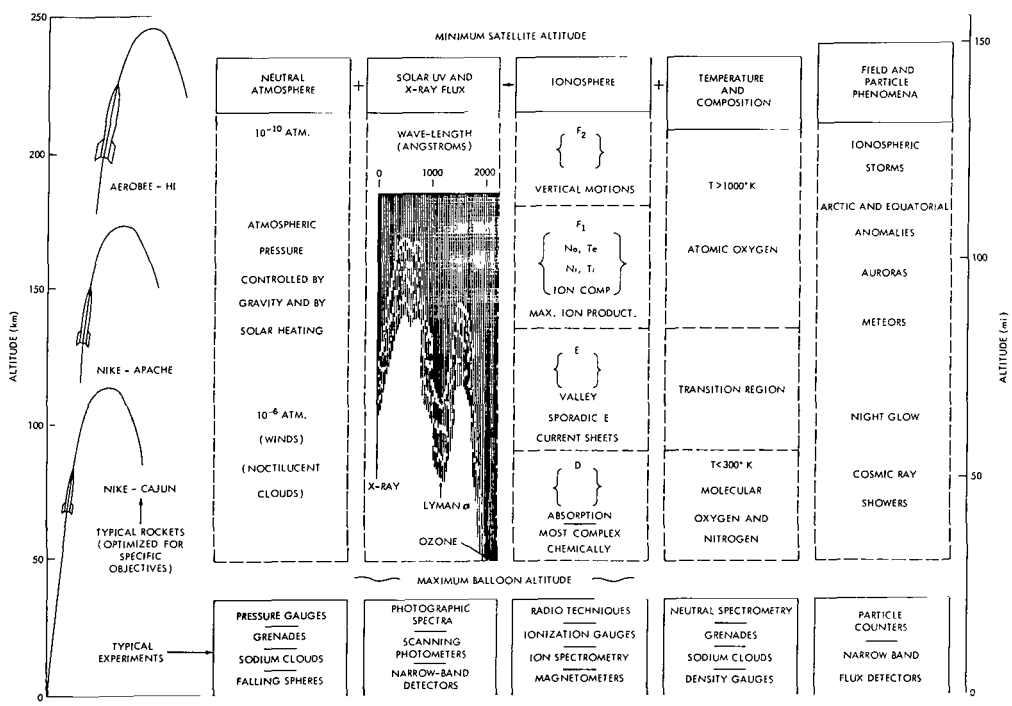


Figure 1—Basic research requiring low altitude sounding rockets.

For the payload to be described herein, it was found desirable to use a lower frequency of 24.53 Mc, thus giving a harmonic factor of only 3, since at this frequency efficient, simple "shroud" antennas proved to be feasible (Reference 6). The loss in measurement-sensitivity by using a frequency of 24.53 Mc, however, can be offset largely by making use of a spinning rocket as shown later. Furthermore at this frequency a number of simplifications can be introduced in the data analysis.

GENERAL PRINCIPLES OF THE CW PROPAGATION EXPERIMENT

The rocket-borne CW propagation experiment introduced by Seddon (Reference 1) is based on the measurement of the dispersive Doppler effect at two harmonically related frequencies f and mf. This Doppler effect arises from the motion of a rocket-borne transmitter within the ionosphere. Because of the splitting of the radio wave into an ordinary and extraordinary mode, each having a characteristic refractive index given by the Appleton-Hartree formula, the Doppler effect will be different for the two modes. The basic quantities measured at the ground are the beat frequencies for each mode, which result from the difference between received high frequency (mf) and low frequency (f) signals. The latter is multiplied by m at the ground before the phase comparison process.

The beat frequencies for the two magneto-ionic components, which are separated at the ground by virtue of their polarization can be expressed by

$$F_{0,x} = \frac{mf}{c}\left[\left(n_{0,x}^{(h)} - n_{0,x}^{(\ell)}\right)\dot{R}_p + \int_0^R \frac{d}{dt}\left(n_{0,x}^{(h)} - n_{0,x}^{(\ell)}\right) dR\right] , \tag{1}$$

where $n^{(h)}$ is the refractive index at the high frequency (mf), $n^{(\ell)}$ is the refractive index at the low frequency (f) and the subscripts 0 and x refer to the ordinary and extraordinary mode, respectively; $\dot{R}_p$ is the velocity component in the propagation direction. The second term will, in general, be negligibly small compared to the first term representing the local refractive index (electron density) except at sunrise and during rapidly changing ionospheric conditions. In any event, the second term can be estimated from simultaneous, ionosonde measurements made during the rocket flight.

Equation 1 represents the beat frequency which would be observed if the rocket were not spinning. For reason of rocket stability, however, a certain spin rate ρ is required which modifies the observed beat frequency:

$$F'_{0,x} = F_{0,x} \pm (m - 1)\rho . \tag{2}$$

At any given time, the roll contribution is added to one mode and subtracted from the other. Since the Doppler shift is of opposite sign during ascent and descent the net effect upon the beat note frequencies depends upon both the direction of the rocket roll and the sign of the Doppler shift.

Assuming the radial velocity component of the rocket with respect to the ground station $\dot{R}$, to be a first approximation to $\dot{R}_p$, the velocity component in the propagation direction, we can rewrite the beat frequency:

$$F_{0,x} = D\left(n_{0,x}^{(h)} - n_{c_x}^{(\ell)}\right) \tag{3}$$

where $D = (mf/c)\,\dot{R}$ is the free space Doppler effect at the high frequency, a quantity which is directly obtainable from the experiment. In Equation 3, $F_{0,x}$ and D are experimentally determined quantities which are obtained during the rocket flight as a function of time (and hence altitude). Equation 3 therefore yields the difference between high and low frequency indices, which determines uniquely the electron density N. In the case when $F_{0,x}$ is relatively large, either as the result of high electron densities, or high rocket velocity or both, the (electronic) combination of ordinary and extraordinary beat frequencies $F_0' + F_x' = F_0 + F_x = F_s$ can be used to simplify the data analysis, since this quantity, according to Equation 1 is independent of the rocket spin (Reference 4). However, in the case of small dispersive Doppler effects which result from the use of $f = 24.5$ Mc and small rockets with relatively low vehicle velocities, the use of F_s is not feasible, since it may correspond to only fractions of 1 cps and the analysis of the resulting data with good height resolution is thus not possible. The details of the data analysis will be discussed.

DESCRIPTION OF THE ROCKET PAYLOAD

The payload consists of two separate sections. The lower section is standard and it is used for the CW propagation experiment, the telemetry and the tracking. The upper section is used for the additional experiments selected. A typical payload is illustrated in Figures 2 and 3 which show the rocket-borne instrumentation used for the first test of the overall system (Nike-Apache flight NASA 14.31). In this case the upper section of the payload was used to perform a Langmuir probe experiment. Space was also available in the upper section for an additional experiment, however, in NASA 14.31 this space was not utilized. The lower section contains the following components: A CW transmitter which

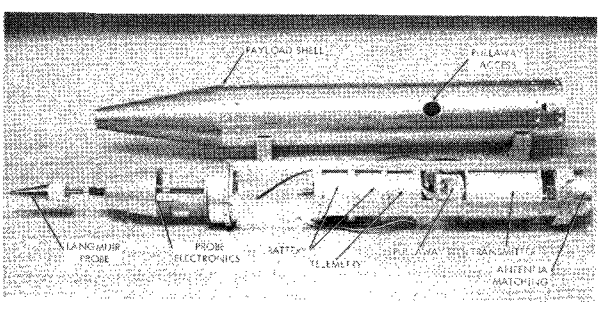


Figure 2—Payload assembly.

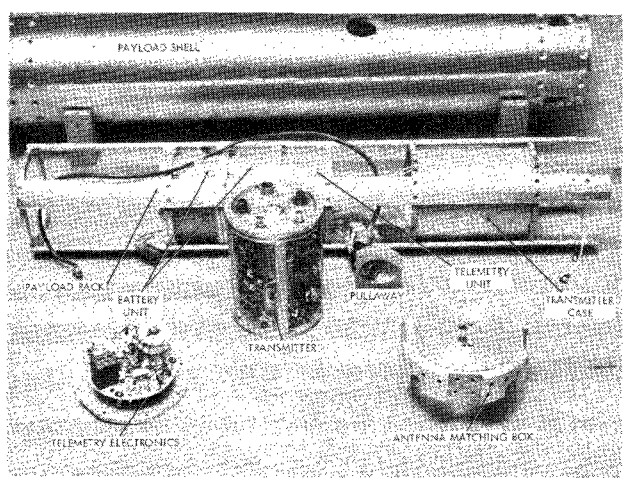


Figure 3—Payload components.

provides two harmonically-related signals at 24.53 and 73.60 Mc; a transmitter-to-antenna matching unit; a telemetry unit; and the flight batteries. The two harmonically related signals are radiated with shroud antennas which are held around the rocket body by means of mounting straps, as shown in Figure 4.

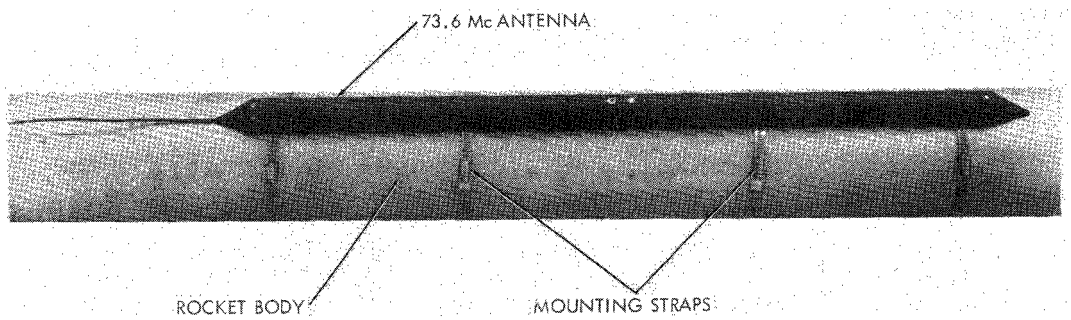


Figure 4—Mounting of shroud antenna.

The transmitter is a transistorized unit built in a pressurized cylindrical case. It was originally designed and used for the P-21 program (References 4 and 5) in which the CW propagation experiment was performed at 12.26 and 73.60 Mc using ARGO D-4 and Scout rockets. The same transmitter is used for the present program with one modification, namely the change of the low frequency from 12.26 to 24.53 Mc. A frequency stability of 1 part in 10^8 was achieved by enclosing the crystal and oscillator circuit in a proportional oven. The transmitter delivers 1.5 w at 24.53 Mc and 0.5 w at 73.6 Mc.

The shroud antennas used for the 24.53 and 73.60 Mc are modified versions of the antennas initially developed by the Ballistic Research Laboratory, Aberdeen, Maryland. These antennas are mechanically very simple, they require no storage space inside the payload and with the modifications made at GSFC (Reference 6) an adequate efficiency can consistently be achieved. The antenna breakdown problem (Reference 7) usually encountered in the 60 to 100 km altitude range has been eliminated by operating the antennas at reduced voltage over this altitude range. Since reliable electron density profiles cannot be obtained at altitudes below 90 km when antenna breakdown is present, the prevention of breakdown is a valuable feature if data are desired at altitudes between 60 and 90 km.

The telemetry is accomplished by modulating the 73.6 Mc signal a total of about 60% with two FM subcarriers having a center frequency of 7.35 kc and 10.5 kc respectively and a ±7-1/2% deviation for a standard 0 to 5 v dc input. The telemetry bandwidth is approximately 100 cycles. The battery consists of 26 nickel-cadmium cells which provide an output of 32 v with a capacity of 1 amp-hr. A dc-to-dc converter is also included to operate the telemetry subcarriers and to furnish any battery voltage required for the additional experiments. The pullaway cable provides a means for charging the batteries, for the pre-flight 1-hr warm-up of the transmitter using external supplies, for monitoring the transmitter output voltages, and for the usual on-off controls of the entire payload. Some leads are also available for monitoring the additional experiments.

The payload dimensions as used for the Nike-Apache flight NASA 14.31 are shown in Figure 5. The total weight of the NASA 14.31 payload, including the additional Langmuir probe experiment, was 32 kg (70 lbs). No effort was made to reduce this weight, since the combined weight and length of the payload were close to optimum from the standpoint of the aerodynamic stability of the rocket. A peak altitude of 167 km was achieved with this payload, in spite of the additional drag introduced by the four shroud antennas.

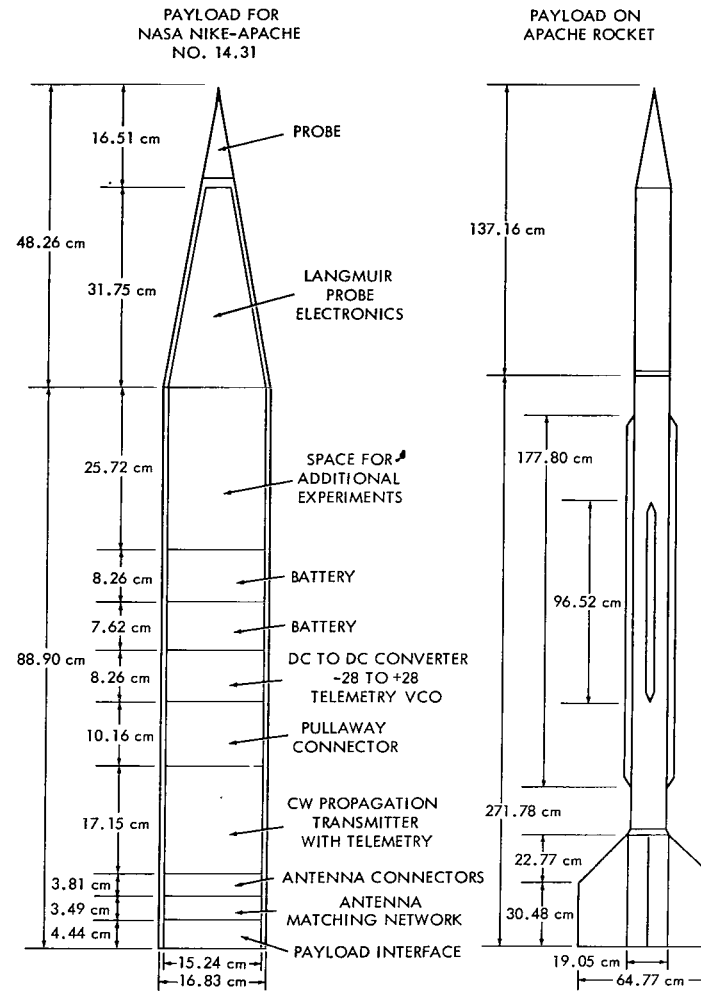


Figure 5—Outline of a typical payload giving location of components and shroud antennas.

DESCRIPTION OF THE GROUND STATION

The ground station is very similar to the receiving site used at Fort Churchill during IGY for the CW propagation experiments conducted by the Naval Research Laboratory (Reference 8). It consists basically of the subsystems shown in the block diagram of Figure 6. They include the receiving antennas, the local oscillator, the 73.6 Mc receivers, the circuits used to derive the 73.6 Mc Doppler shift and the rocket roll, the 24.53 Mc receivers, the circuits used to derive the beat frequency signals $F'_{0,x}$, and the telemetry receiver. In addition, suitable equipment is required to record the experimental data.

The 73.6 Mc and 24.53 Mc signals are each received with an antenna, which is essentially a circularly-polarized Yagi. The 24.53 Mc receiving antenna is fixed in position, and oriented to give maximum gain near the peak of the predicted trajectory. The smaller 73.6 Mc antenna is placed on a movable platform and its orientation is manually adjusted during flight according to the predicted look angle. A Magic-T (Reference 8) is used with each antenna in order to detect both polarization modes. The ordinary and extraordinary modes are then fed into separate receiving systems.

In view of the unusual requirements placed upon the local oscillators, this function is performed by a separate unit. The local oscillator provides the first of the two reference signals used at the

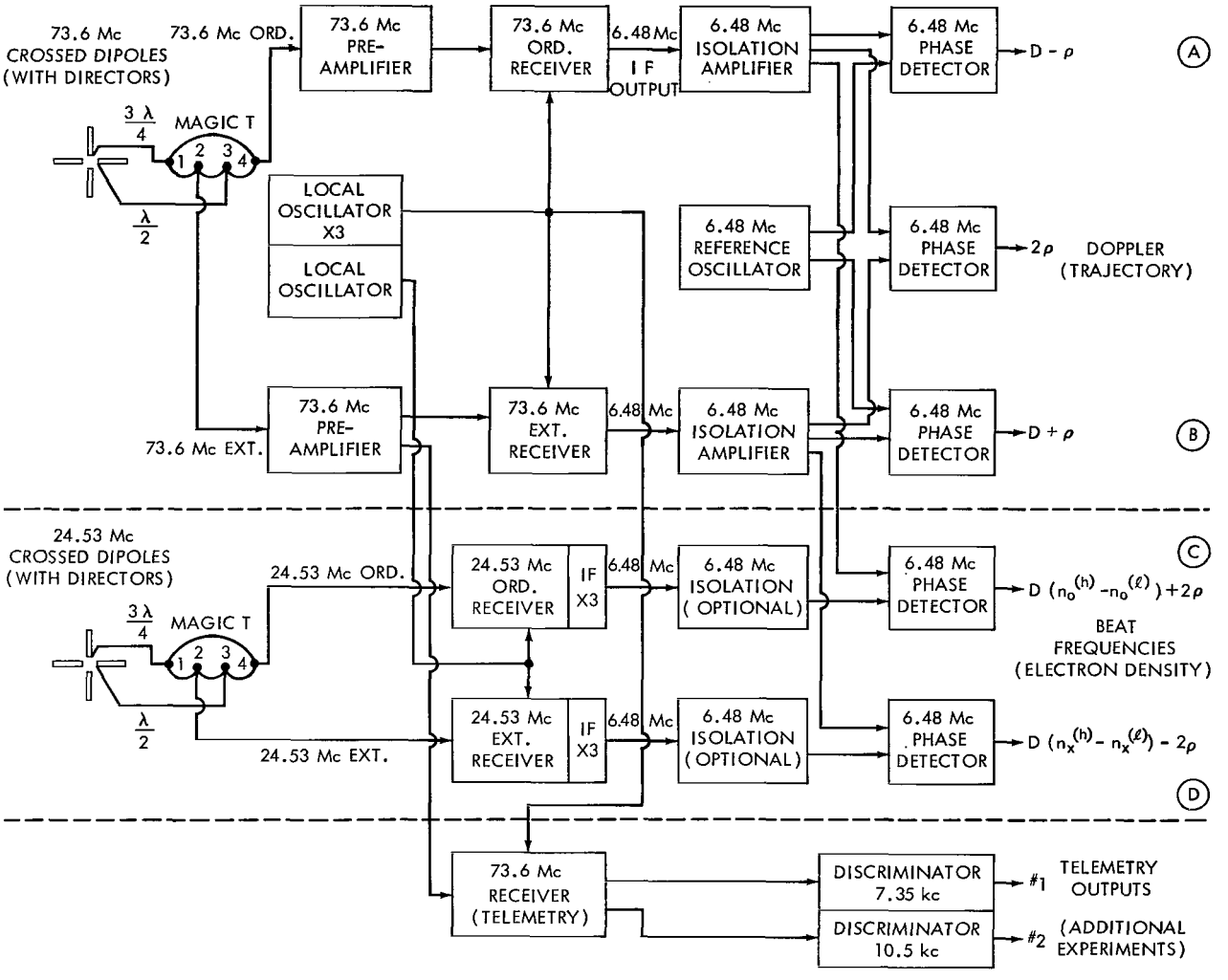


Figure 6—Block diagram of the ground station for the 24.53/73.60 Mc propagation experiment.

ground station for the Doppler measurement. An accurate Doppler measurement requires the local oscillator to maintain a stability of at least 1 part in 10^9 during the rocket flight. This stability is achieved with a crystal-controlled circuit which is enclosed in a well-regulated oven. A careful mechanical design also contributes to this stability. A high-quality capacitor is used to modify slightly the crystal frequency which makes it possible to adjust the Doppler signal to its initial pre-launch zero value. The amount of frequency-control available in this manner is about 0.002%. If the presence of radio interference requires some additional frequency shift, this is accomplished by replacing the crystals both in the transmitter and in the ground station local oscillator. The local oscillator unit provides outputs harmonically related in a 3-to-1 ratio. The low frequency outputs serve as local oscillators for the two 24.53 Mc signals and the high frequency outputs serve as local oscillators for the three 73.60 Mc receivers.

The two 73.6 Mc receivers used for Doppler measurement and for the CW propagation experiment convert the input signals to a 6.48 Mc IF frequency. The use of crystal filters in the IF amplifier yield a net receiver bandwidth of 2.5 kc which is more than adequate to accommodate the change in input signal frequency due to Doppler shift. This narrow bandwidth eliminates the telemetry subcarrier, and minimizes noise and radio interference. The receivers use automatic gain control (AGC); the AGC voltage is also recorded during flight to provide a measurement of signal strength. The output of each of these 73.6 Mc receivers is a CW signal at 6.48 Mc whose amplitude is maintained at approximately one volt by the combined action of the AGC and of a voltage limiter, for input signals to the 73.6 Mc pre-amplifier ranging from 0.1 to 1000 mv. The constant amplitude output is required for the proper operation of the subsequent phase comparison circuits. A pre-amplifier is used ahead of the 73.6 Mc receiver to provide additional gain. The pre-amplifier has a nominal 52 ohm input impedance, which can be adjusted resistively and reactively to provide precisely the impedance required for the optimum operation of the Magic-T.

The 6.48 Mc outputs of the 73.6 Mc ordinary and extraordinary receivers have the following frequencies:

$$f_H - n_0^{(h)} D + \rho - f_0 \tag{4}$$

and

$$f_H - n_x^{(h)} D - \rho - f_0 \ , \tag{5}$$

where f_H = frequency of 73.6 Mc signal as transmitted from the rocket, $n_0^{(h)} D$ = 73.6 Mc Doppler shift for the ordinary mode, $n_x^{(h)} D$ = 73.6 Mc Doppler shift for the extraordinary mode, ρ = rocket roll, and f_0 = local oscillator frequency. Direct comparison of the signals given by Equations 4 and 5 yields:

$$2\rho + D\left(n_0^{(h)} - n_x^{(h)}\right) = 2\rho + \text{Faraday rotation at 73.6 Mc} \ .$$

For ionosphere experiments using small rockets the 73.6 Mc Faraday rotation is less than 0.1 cps whereas 2ρ is generally 10 cps. Thus comparison of Equations 4 and 5 yields the rocket roll with an accuracy better than 1%.

The signals (Equations 4 and 5) are also individually compared to a 6.48 Mc reference oscillator whose frequency is actually $f_H - f_0$, and whose frequency stability is 1 part in 10^9. This yields the following difference frequencies:

$$n_0^{(h)} D - \rho \approx D - \rho \tag{6}$$

and

$$n_x^{(h)} D + \rho \approx D + \rho \ . \tag{7}$$

Since the frequency of the Doppler signal is in general too high for direct reading from the record, commercial decade counters are used to divide the Doppler signals. Decade counters are also used to generate the timing signals, from the output of a timing oscillator.

Addition of Equations 6 and 7 yields the roll free Doppler shift at 73.6 Mc:

$$D\left(n_0^{(h)} + n_x^{(h)}\right) \approx 2D \ . \tag{8}$$

At 73.6 Mc the two indices are very nearly equal to each other and for rocket flights below 180 km their values will range from 1.0 in free space to about 0.96 corresponding to a density of 5×10^5 electrons/cm^3. Thus, the sum of Equations 6 and 7 yields essentially the correct Doppler shift at altitudes below 100 km and at higher altitudes a correction amounting to a few percent can be made for the ambient local electron density. This ambient density can be initially calculated with less than 5% error by using the approximation given in Equation 8. This first calculation of electron density is adequate to determine D more accurately. If desired the process can be repeated for additional accuracy, but this is usually not necessary.

The 24.53 Mc receivers are very similar to the high frequency receiver. In this case the impedance matching to the Magic-T is accomplished at the input of the receiver (since a pre-amplifier is not used). The crystal filters used in the IF amplifier produce a net receiver bandwidth of 800 cps. The outputs of IF amplifiers after frequency multiplication by a factor of 3 yield signals whose nominal frequency is 6.48 Mc. The actual frequency of the output signals are

$$3\left[\frac{f_H}{3} - n_0^{(\ell)}\frac{D}{3} + \rho - \frac{f_0}{3}\right] = f_H - n_0^{(\ell)} D + 3\rho - f_0 \tag{9}$$

and

$$3\left[\frac{f_H}{3} - n_x^{(\ell)}\frac{D}{3} - \rho - \frac{f_0}{3}\right] = f_H - n_x^{(\ell)} D - 3\rho - f_0 \tag{10}$$

These signals are compared to the corresponding ordinary and extraordinary outputs given by Equations 4 and 5 of the 73.6 Mc receivers and two difference signals are obtained having the frequencies

$$F_0' = D\left(n_0^{(h)} - n_0^{(\ell)}\right) + 2\rho$$

and

$$F_x' = D\left(n_x^{(h)} - n_x^{(\ell)}\right) - 2\rho \ .$$

A third 73.6 Mc receiver is used for the telemetry. This receiver is identical to the two other 73.6 Mc receiver except for the fact that crystal filters are not used in the IF amplifier. This provides a 50 kc bandwidth which is adequate for the reception of the telemetry sub-carrier.

A certain amount of test equipment is required to adjust the various components of the ground station and to check the overall operation. Some of the necessary equipment is available commercially such as impedance bridges and signal generators. A commercial frequency counter is also highly desirable. Special test equipment has been designed at GSFC to adjust and check the crystal filters used in the 24.53 and 73.6 Mc receivers. Since commercial signal generators are not sufficiently stable to simulate the input 24.53 and 73.6 Mc signals, special test generators have also been designed for this purpose.

USE OF DOPPLER DATA FOR TRAJECTORY DETERMINATION

If the ground station for the CW propagation experiment is located within 1 or 2 km from the launch site, the ground station Doppler data can be used to calculate small rocket trajectories (Reference 9) if the payload transmitter maintains a stability of the order of 1 part in 10^8. The rocket borne transmitter has a stability of 1 part in 10^9 in the laboratory and during ballistic flight its stability is at least 1 part in 10^8. During the propulsion period some difficulties have been experienced in maintaining the required 1 part in 10^8 stability. However it is anticipated that this can be achieved in the near future as a result of further refinements currently under investigation. The uncertainty of the trajectory determination (assuming a stability of at least 1 part in 10^8 in the Doppler data) is about $\pm 1\%$ of the maximum altitude in absolute altitude which is adequate for most purposes. The relative altitudes in a given region of interest are, of course, known with far greater accuracy and consequently profiles of the measured ionospheric parameters will not be appreciably distorted by the small uncertainty in the absolute altitude. Radar data for six rocket flights at Wallops Island have been used to check the accuracy of trajectories determined from the corresponding Doppler values. It was found that correct Doppler data would have yielded trajectories accurate to within 1 km at altitudes above 70 km. A study made by Seddon* indicates that the errors are slightly larger if launching is in a direction other than towards the East as was the case at Wallops Island. In any event, the payload can be used with Seddon's SSD system (Reference 10) if higher accuracy is desired for the trajectory. Alternately corrections could be made to the approximate trajectory based upon the azimuth of the rocket flight.

The method is based upon the following approximations which are valid for rockets such as the Nike-Cajun and the Nike-Apache which have peak altitudes less than 200 km:

1. Earth curvature and rotation can be neglected;
2. The trajectory is in a plane which contains the launch site; and

*J. C. Seddon, Private communication.

3. If the ballistic portion of the trajectory is extended below the drag region, that is for altitudes below 70 km, the extension of the trajectory (assuming no drag) will intersect the ground within a few kilometers of the launch site and of the nearby ground station.

A more complete presentation of the technique, is given in Reference 9.

These assumptions are illustrated in Figure 7. Under these conditions the trajectory above 70 km is defined by the following equations, where the coordinate system is that shown in Figure 7:

$$X = X_0 + \dot{X}t, \quad (\dot{X} = \text{constant}) , \tag{13}$$

$$Z = Z_0 - g_0 \frac{t^2}{2} \left(1 + \alpha t^2\right) , \tag{14}$$

where X is the horizontal distance, X_0 is the distance from launch to sub-peak point (i.e., equal to the horizontal distance at peak), $\dot{X}$ is the horizontal velocity, Z is the altitude, Z_0 is the peak altitude, $\alpha = 2.42 \times 10^{-7}/\text{sec}^2$ for typical small rocket trajectories, $g_0 = g_e R_e^2/(R_e + Z_0)^2$ is the value of g at peak, g_e is the value of g at the ground, and R_e is the earth's radius. The term involving α takes into account the variation of g the acceleration of gravity with altitude. Since g_0 is related to Z_0, the unknowns are actually X_0, $\dot{X}$, Z_0 and the peak time (i.e., the number of seconds elapsed since rocket take-off).

The fact that the extension of the ballistic trajectory is assumed to intercept the launcher leads to

$$X_0 = \dot{X}T ,$$

where T is the total free fall time from Z_0 to the ground, a quantity which is less than the peak time. Since

$$Z_0 = g_0 \frac{T^2}{2} \left[1 + \alpha T^2\right] ,$$

the following relationship holds between Z_0 and X_0:

$$Z_0 = g_0 \frac{X_0^2}{2\dot{X}^2} \left[1 + \alpha \frac{X_0^2}{\dot{X}^2}\right] . \tag{15}$$

The Doppler measurement at 73.60 Mc yields the quantity $D = 245.3\,\dot{R}$ cps (where $\dot{R}$ is in km/sec) from which the radial velocity $\dot{R}$ and the radial distance R can be calculated.

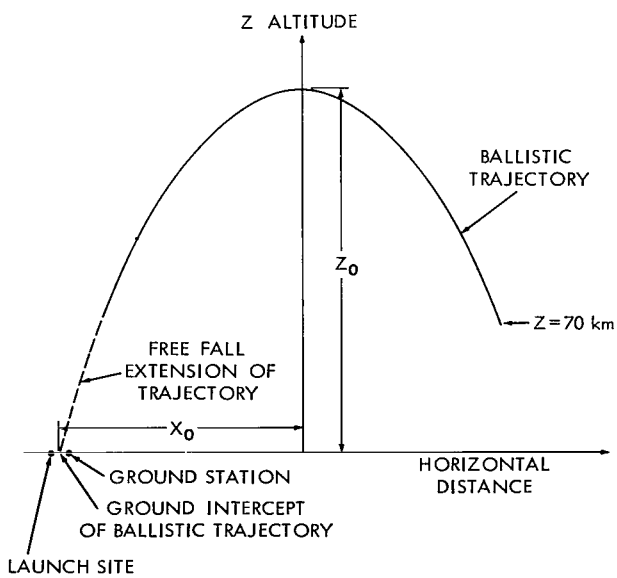


Figure 7—Geometry of typical small rocket trajectory.

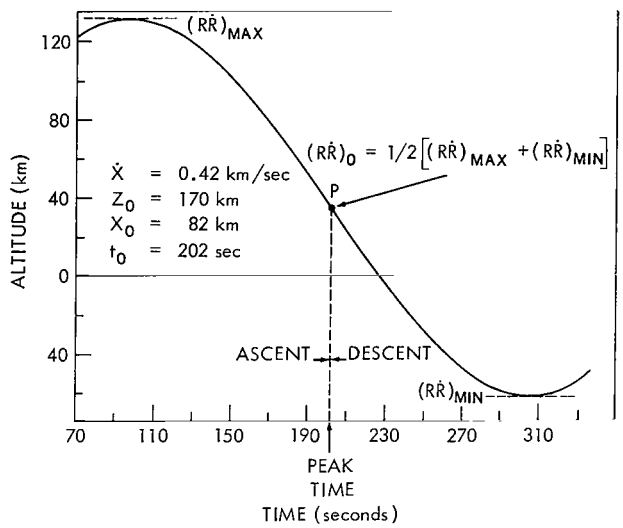


Figure 8—The $R\dot{R}$ function for a typical Nike-Cajun trajectory.

These are related to X and Z in the following manner:

$$R^2 = X^2 + Z^2 \; ; \tag{16a}$$

$$R\dot{R} = X\dot{X} + Z\dot{Z} \; . \tag{17a}$$

The trajectory determination is based upon the relationships of Equations 15, 16, and 17. The calculation is done in two steps:

First the peak time is obtained by making use of the fact that the graph of $R\dot{R}$ versus time is symmetrical with respect to the peak (Reference 9). A plot of $R\dot{R}$ versus time is shown in Figure 8 for the portion of the trajectory which is above 70 km. The value of $R\dot{R}$ at the peak of the trajectory is

$$(R\dot{R})_0 = \frac{1}{2}\left[(R\dot{R})_{max} + (R\dot{R})_{min}\right] \; .$$

This expression yields the ordinate of point P on the graph, and with point P located, the corresponding abscissa is the peak time t_0. Knowing the peak time, we can readily obtain the corresponding radial distance R_0 which gives the following equation between X_0 and Z_0:

$$R_0^2 = X_0^2 + Z_0^2 \; . \tag{16b}$$

Also at peak, Equation 17 reduces to

$$(R\dot{R})_0 = X_0\dot{X} \; . \tag{17b}$$

The calculation of Z_0, X_0 and $\dot{X}$ can then be performed by solving simultaneously Equations 15, 16b, and 17b. This system of equations can be solved analytically very rapidly (Reference 9) by a method which makes use of successive approximations to the correct value of g_0 and also makes use of one additional experimental value of the quantity $R\dot{R}$. A simpler method is to use a graph showing the value of Z_0 as a function of $(R\dot{R})_0$ and R_0. Such a graph is shown in Figure 9.

ANALYSIS OF THE CW PROPAGATION EXPERIMENT

For the data analysis of the present experiment, it has been found advantageous to make use of the normally unwanted rocket spin. Small rockets, of the Nike-Apache type usually require a spin of $\rho \approx 5$ cps to insure proper rocket stability. Because of the relatively low vehicle velocity

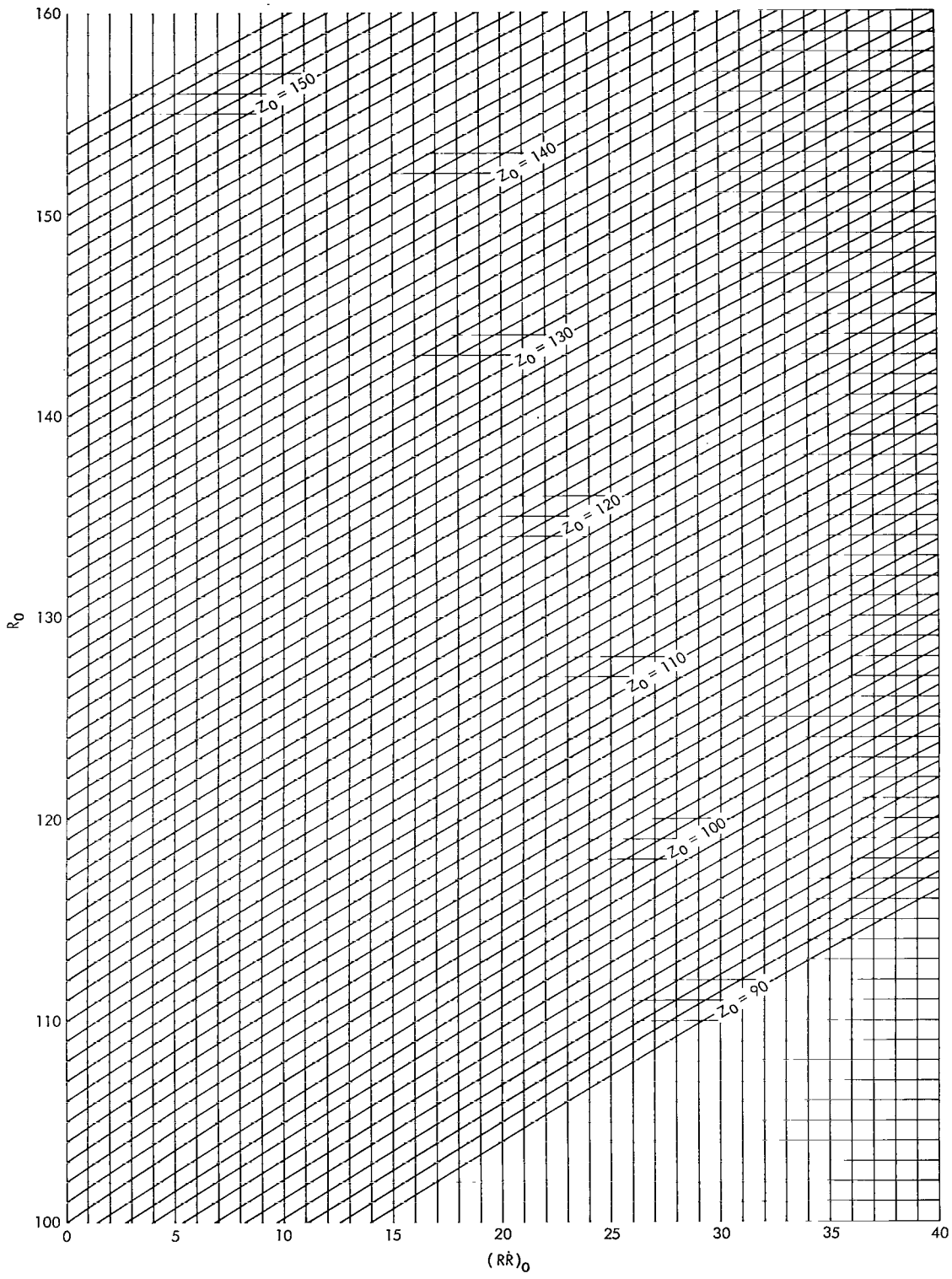
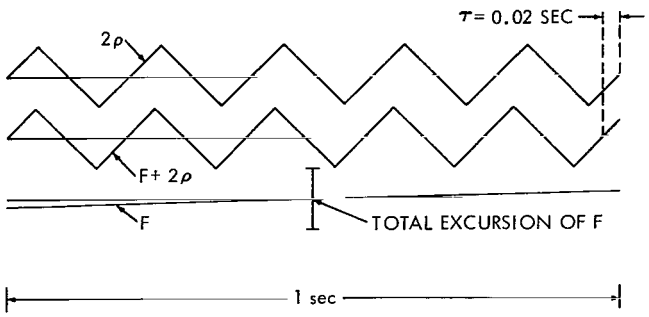


Figure 9—Nomogram giving the peak altitude as a function of $(R\dot{R})_0$ and R_0.



FREQUENCIES ASSUMED AS FOLLOWS: $2\rho = 5$ cps; $F = 0.1$ cps
RESOLUTION IN MEASURING τ IS 0.001 sec

Figure 10—Detection of very low frequency beats with the aid of rocket roll.

combined with the use of a relatively high frequency (24.53 Mc), the quantity F in Equation 2 will usually be much smaller than 2ρ. The latter quantity is also obtained directly by comparing the ordinary and extraordinary propagation modes at 73.6 Mc. Since the accuracy in time measurements is of the order of 0.001 sec, a time difference as small as 0.01 sec can still be measured with sufficiently high accuracy. For this reason the rather small quantity F can be measured by comparing the period of 2ρ with that of $F' = F \pm 2\rho$. The basic method of measuring the beat frequency F in this manner is illustrated in Figure 10, where the following assumptions were made: $F = 0.1$ cps and $2\rho = 5$ cps. The time difference in the periods of F' and 2ρ correspond in this case to 0.02 sec which can be measured with sufficiently high accuracy over a 1 sec interval which is desirable for proper height resolution.

The actual case is somewhat different from the idealized case described above since the observed spin rate 2ρ is not uniform (Reference 11), but shows a modulation due to the changing aspect. It is therefore necessary to read data over complete roll periods or multiples to assure the same aspect and phase. Some actually recorded data of roll and beat frequency are shown in Figure 11, which corresponds to a flight where the rocket axis was very nearly pointed toward the ground station. Figure 12 shows data for the Nike-Apache flight NASA 14.32 illustrating the effect of poor aspect on the roll frequency. The interval A-B on the 4ρ signal corresponds to a full roll period; it contains two fast and two slow cycles. The interval C-D corresponding to a higher altitude reveals a shift in the zero-crossings of F_0' and F_x' which are due to the total electron content between the altitudes corresponding, respectively, to intervals A-B and C-D.

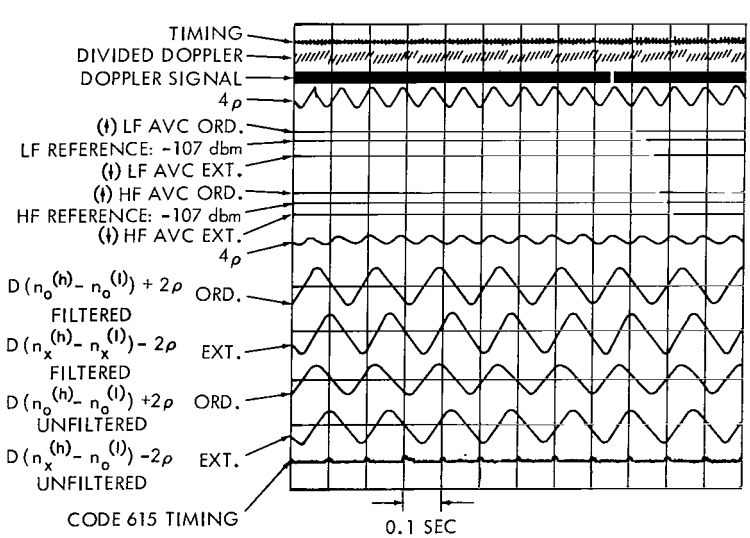


Figure 11—Sample recording of CW propagation data.

The determination of F from F' by comparing this quantity with 2ρ can obviously be made for both the ordinary and extraordinary mode, thus increasing the measurement accuracy. The sum-beat-frequency $F_s = F_0 + F_x$ can also be obtained by combination of the periods T_0' and T_x' of F_0' and F_x' to give

$$F_s = \frac{T_0' + T_x'}{T_0' \, T_x'} .$$

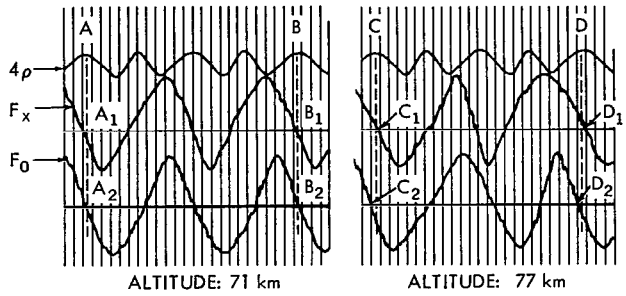


Figure 12—Sample recording showing roll-modulated beat frequencies for NASA 14.32.

Finally, for deriving the electron density N from the beat frequencies F_0, F_x or F_s, it is convenient to represent the appropriate linear combination of refractive indices of high and low frequency (which are individually computed from the complete Appleton-Hartree formula) graphically as a function of N with parametric values for the magnetic field H and the angle between the propagation direction and H. For the low altitude flights under consideration, an effective value of H can be assumed, since the magnetic field does not change significantly over the first 200 km altitude interval. By using the high accuracy in time measurements of the periods corresponding to the beat frequencies $F_{0,x}$, it is possible to obtain a resolution of about 500 electrons/cm^3 in the determination of electron density, using frequencies of 24.53 Mc and 73.6 Mc and a rocket of the Nike-Apache type.

From the viewpoint of easier data analysis it is desirable to locate the ground station near the launch site. In this case the aspect of the rocket antennas will generally be good at least on the upward leg of the trajectory and for this portion of the trajectory the propagation path will fall essentially along the rocket trajectory.

As a first approximation to Equation 1, it was assumed in Equation 2 that the rocket velocity component in the propagation direction $\dot{R}_p$ is identical to the radial velocity component of the rocket, $\dot{R}$. At the relatively high frequencies used in this experiment this is a reasonably good approximation for the lower part of the trajectory. However, with more oblique propagation paths in the uppermost portion of the trajectory and especially on the downleg, this ceases to be true and a correction for this effect is required. In essence, this correction is equivalent to a first-order refraction correction to account for the effect of the ionosphere, which causes the ray direction of the radio wave to depart from the radial direction of the rocket velocity component. Although the correction would essentially require a ray-tracing procedure, a simple first-order correction of the type outlined below has been found to be sufficiently accurate for low altitude rockets. If N′ is the electron density derived from the beat frequency F, assuming $\dot{R}_p = \dot{R}$, the true electron density N taking into account the effect of obliquity (refraction) is given by (Reference 4)

$$N = N' + \frac{\epsilon}{1 - \epsilon} (N' - \bar{N}) ,$$

with $\epsilon = (\dot{\theta} R \tan\theta)/\dot{R}$, where θ is the zenith angle of the rocket position vector at the ground station, R is the radial distance between rocket and ground station and $\dot{R}$ is the radial velocity component, quantities which can be obtained from the trajectory data, and where

$$\bar{N} = \frac{1}{R}\int_0^R N dR \approx \frac{1}{R}\int_0^R N' dR$$

Inclusion of the above correction is equivalent to using the rocket velocity component $\dot{R}_p$ along the ray path as discussed by Kelso (References 12 and 13). The above analysis yields reliable electron density profiles up to an altitude within 5 to 10 km of apogee. For close-to-apogee altitudes a detailed ray-tracing analysis including a correction for the time variation in the ionosphere would be required, an effort which, in general, is not warranted for such a small height interval.

RESULTS

Two Nike-Apache flights (NASA 14.31 and 14.32) have been made from Wallops Island, Virginia late in 1962 to test the operation of the described payload, both of which were completely successful. In Figure 13 the CW signals received as a function of range are shown. It is obvious that the shroud antennas provided efficient radiation for performing the CW propagation experiment, the Doppler effect measurements, as well as the telemetry mission. The field strength on the ground at the two frequencies were about 4 μv/m for a maximum slant range of about 180 km.

Figure 14 shows the electron density profiles obtained from the CW propagation experiment for the two flights. The percent obliquity correction $(N-N')/N$ at 120, 140 and 160 km was 1, 7 and 17% for profile A, and 1, 3 and 7% for profile B, respectively. It should be noted that

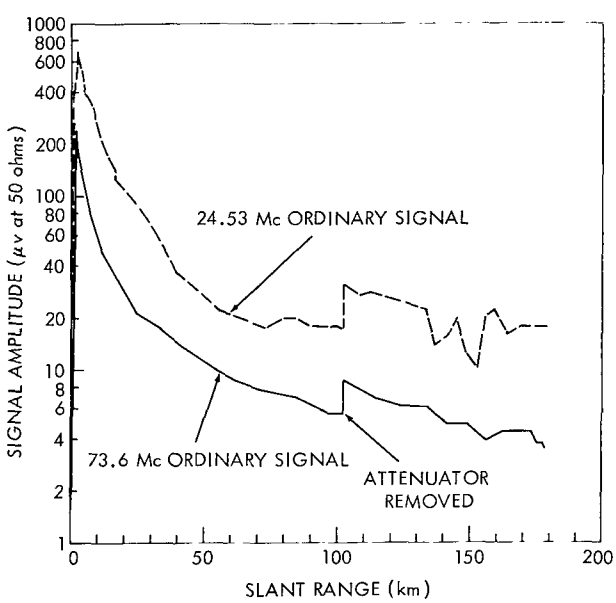


Figure 13—Amplitude of received signals during a test flight of NASA 14.32.

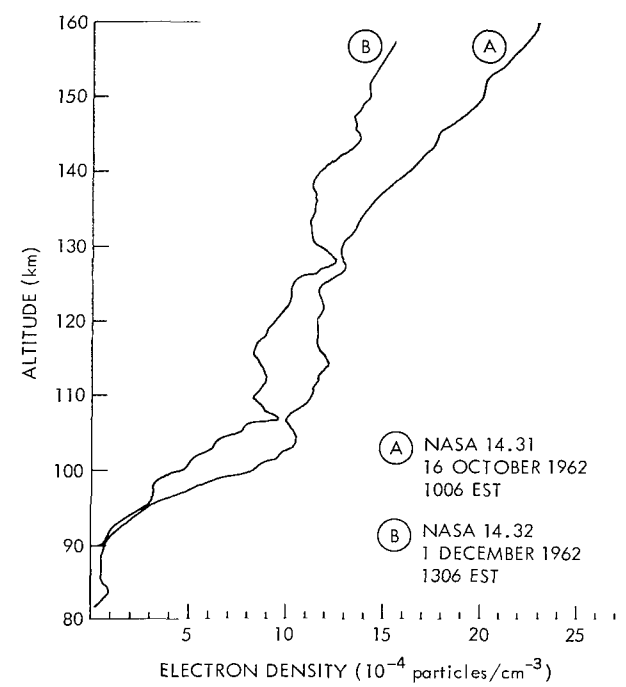


Figure 14—Electron density profiles obtained during the two test flights.

these two mid-day profiles at mid-latitudes indicate once more the absence of a significant "valley" in the electron density distribution between the E and F regions as had been observed in earlier experiments (Reference 14).

In Figure 15 the electron density profile obtained with the CW propagation experiment is compared with a current profile obtained from L. G. Smith's asymmetric Langmuir probe experiment which occupied some of the remaining payload space on NASA 14.31. The Langmuir probe current scale has been normalized to match the CW propagation profile. In order to yield absolute values of electron density, the Langmuir probe data require an experimental calibration such as the one shown in Figure 15. The validity of this calibration under all ionospheric conditions remains to be established. In addition, electron densities obtained from a true-height analysis of the Wallops Island ionosonde observations at flight time are shown, indicating a departure from the rocket profiles at altitudes below 120 km, which is obviously the result of the lack of ionosonde measurements for the lowermost ionosphere.

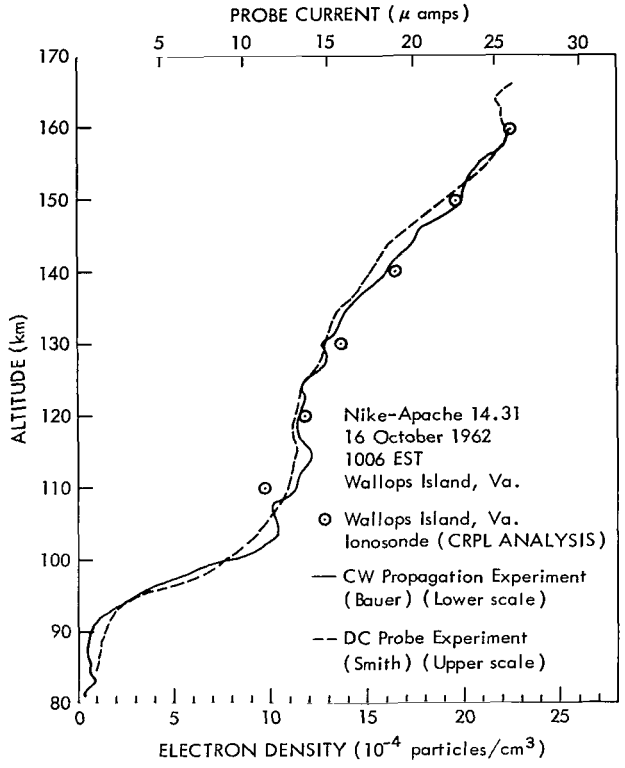


Figure 15–Comparison between electron density profiles obtained simultaneously by two different techniques.

CONCLUSION

The small payload for ionosphere studies described in this paper has been successfully tested on two Nike-Apache rockets. Its versatility, simplicity and relatively low cost should make this payload an ideal tool for the investigation of many problems of the ionospheric E and F regions by the international scientific community, especially during the International Year of the Quiet Sun. Useful electron density measurements throughout the D-region appear also feasible as the results of the development of a 12 Mc shroud antenna which is presently under investigation. The details of the design of the payload and ground station will be made available to all interested experimenters upon request.

ACKNOWLEDGMENTS

Mr. G. H. Spaid and Mr. J. R. Hagemeyer have been responsible for the design of the payload and ground station as well as for the supervision of the field operations for the two rocket flights.

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