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DETERMINATION OF THE RATE OF ROLL OF PILOTLESS AIRCRAFT RESEARCH MODELS BY MEANS OF POLARIZED RADIO WAVES

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DETERMINATION OF THE RATE OF ROLL OF PILOTLESS AIRCRAFT RESEARCH MODELS BY MEANS OF POLARIZED RADIO WAVES

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SUMMARY

A method is presented for determining the rate of roll of free-flight aerodynamic models by means of polarized radio waves. A discussion of the technique used and a description of the equipment are included. The discussion shows that through the use of this technique the direction of roll, as well as zero roll, is uniquely determined. Analysis of the data obtained and data accuracy are discussed and examples are given to show how the record-reduction method affects the accuracy of the data. In conclusion, a method for increasing the accuracy and reducing work-up effort is discussed.

INTRODUCTION

The National Advisory Committee for Aeronautics has adopted an aerodynamic research technique, for investigations in the supersonic speed range, which utilizes free-flight rocket-powered aerodynamic test vehicles. In some of the investigations conducted by this method, such as those for determining control effectiveness, some means for measuring the rate of roll of the model in flight was required. Existing methods of measuring spin, such as used for determinations of artillery-shell spin decay (reference 1) were not suitable. Excessive errors when the rate of roll is low and the angular acceleration high and ambiguities which occur when roll changes direction made the development of a new technique necessary.

This paper discusses a measurement technique which was derived from the fact that the voltage induced by a polarized radio wave in a receiving dipole, parallel to the arriving wave front, is proportional to the cosine of the angle which the plane of polarization makes with the dipole.

DESCRIPTION OF TECHNIQUE

Consideration of this polarization effect made it appear feasible to install a continuous-wave radio transmitter in an airborne body and record the change in received signal strength with the aid of an amplitude detector. Thus, as the body rotated about an axis through the antenna and the aircraft, the detected signal would serve as a measure of angular displacement. However, consideration of the principles involved made it apparent that determination of the direction of roll was not possible and, if the vehicle stopped rolling, no usable data were obtained. This difficulty was overcome and the technique made useful by the addition of a rotating antenna at the ground receiving station. The receiving antenna was rotated at a constant speed so that if the rate of roll were zero, the fundamental recorded frequency was equal to twice the antenna rotational frequency, because the antenna lined up with the polarization plane twice per revolution. If the roll were opposite in direction to the antenna rotation, the recorded frequency increased and, if it were in the same direction, it decreased.

Best results are obtained when the propagated wave arrives at the receiving antenna with uniform field distribution and when the antenna rotates in a plane which is parallel to the wave front of the arriving field. It was found that these specifications are more nearly realized when the vehicle is launched at a high angle of elevation, from a site as closely adjacent to the antenna position as practicably possible and the rotating antenna, in turn, is aimed so that the rotation plane is approximately perpendicular to the flight path.

Firing the test vehicle at high angles of elevation accomplishes two desirable effects: First, the vehicle rapidly leaves the influence of the earth, from the standpoint of radio-wave propagation; thus, the wave front arriving at the antenna becomes a closer approximation to one in free space. Second, the trajectory more nearly approaches a straight-line flight path during the first part of the flight so that the wave-front orientation remains approximately parallel to the plane of antenna rotation. Failure to observe these precautions results in serious wave-form distortion of the recorded roll signal.

DESCRIPTION OF EQUIPMENT

Airborne Unit

The aerodynamic model design requirements included the installation of a light-weight, continuous-wave transmitter. The transmitter employed (fig. 1) is essentially the same as the spinsonde developed at the

Applied Physics Laboratory for ballistic spin measurements. This unit is made a complete nose assembly (fig. 2) by "potting" it in a plastic dielectric in such a manner that the metal fairing and tip are integral with the potting material. The complete assembly of a typical roll research model is shown in figure 3.

Radiation of radio-frequency energy takes place at approximately 160 megacycles by means of the V-shape conductors which also serve as the resonant circuit of the transmitter. The radiation of interest is along the roll axis in a rearward direction. The field strength as found from radiation patterns proved to be essentially uniform over a wide solid angle in this region. In addition, this radiation is essentially plane-polarized along the roll axis.

Ground Equipment

The rotating antenna and receiving station are shown in figures 4 and 5. The receiving dipole is imbedded in a streamline wooden fairing to reduce aerodynamic drag. The rotating drive shaft is smooth-gun-bored and silver-plated on the inner surface. A center conductor is supported in the center of the shaft with solid dielectric so that the shaft serves as a coaxial transmission line from the dipole to stationary brushes. The center conductor is cut so that the antenna impedance is properly matched. The antenna is driven mechanically at 3450 rpm by means of an induction motor through a suitable gear box. The assembly can be aimed manually and locked at any desired angle of elevation and azimuth, this feature of the over-all instrumentation system being very desirable.

The receiving station (fig. 5) consists primarily of a suitable VHF receiver and oscillograph recorder with associated electronic circuits and power supplies necessary for the proper operation of the system.

SYMBOLS

e_s	instantaneous modulation voltage
$E_s(t)$	peak amplitude of modulation wave form as a function of time
Δ	absolute errors in quantity it precedes
K	constant (1, 2, 3 . . .)
N_r	number of cyles of relative roll signal during a time interval t_r

N_m number of missile rotations during a time interval t_r

N_a number of antenna rotations during time interval t_r

t_r time interval (increment) for N_r cycles, seconds

ϵ_m maximum relative error in angular velocity of missile

ω_r relative angular velocity of detected roll signal, radians per second $(K(\omega_a - \omega_m))$

ω_m angular velocity of vehicle, radians per second

ω_a angular velocity of antenna, radians per second

ω_s angular velocity of vehicle relative to antenna, radians per second $(\omega_a - \omega_m)$

ANALYSIS

General

As pointed out in the introduction, the radio-frequency signal received on the ground becomes amplitude modulated by the angular rotation of the polarized wave relative to the receiving dipole antenna. This modulation wave form may be expressed for purposes of analysis by the series equation

$$e_s = E_s(t)\left[\frac{2}{\pi}\left(1 + \frac{2}{3}\cos 2\omega_s t - \frac{2}{15}\cos 4\omega_s t + \ldots\right)\right] \tag{1}$$

where ω_s is the angular velocity of the aerodynamic model relative to the rotating antenna and $E_s(t)$ is the peak amplitude which is expressed as a function of time to account for changes with time due to variations in field strength, receiver gain, and other pertinent factors.

Expression (1) may be visualized as a full-wave-rectified sine wave of varying amplitude; therefore, if this wave form is passed through a band-pass filter, so that the fundamental is retained, it will have an angular rate ω_r equal to twice the angular rate of the model with respect to the antenna ω_s. The frequency of the relative roll signal has thus been multiplied by a factor of two.

A sample part of a record is shown in figure 6 and the various signals appearing are identified thereon. The relative roll signal

marked "second-detector output" shows very good correlation with equation (1) when consideration is given to such factors as:

(a) Departure of wave from plane polarization

(b) Multiple path reflections

(c) Noise

(d) Departure of wave-front plane from antenna plane

The peaks of this wave nearest the edge of the record occurred when the antenna and polarized field were in alinement and the opposite peaks occurred when they were in quadrature.

The same relative roll signal after being amplified and filtered is also seen in figure 6. The reduction of noise which is apparent becomes more important when the signal-to-noise ratio in the second-detector output is very low. The presence of a phase shift is noticeable but is unimportant because it remains essentially constant.

A positive pip is recorded each time the antenna makes a revolution, as shown in the antenna-position signal (fig. 6), to provide the time history of angular displacement of the antenna. This time history is needed in order that the vehicle roll can be determined from the relative roll.

Data Reduction

The record (fig. 6) is a time history of angular displacement of the test vehicle with respect to the rotating antenna. In order to convert this data into rate of roll, a numerical differentiation must be performed in a manner that removes the antenna angular velocity from the relative roll. Displacement differentiation, in general, consists of taking ratios of small displacement increments to the corresponding time intervals; angular velocity thus obtained is subject to all errors attendant upon such a procedure, such as errors in displacement-interval measurement and time-interval determination.

An evaluation of these angular-displacement errors can be made by first considering the relationship

$$\omega_m = \omega_a - \frac{\omega_r}{K} = \frac{2\pi N_a}{t_r} - \frac{2\pi N_r}{Kt_r} \tag{2}$$

where K is used to account for any electronic multiplication of the

recorded-roll-signal frequency, ω_a is the antenna angular velocity in radians per second, ω_m is the vehicle rate-of-roll in radians per second, and ω_r is the relative angular velocity in radians per second. If no other electronic multiplication is performed, $K = 2$ as in equation (1). Taking the total differential of equation (2) and dividing by ω_m gives the following expression for the relative error:

$$\epsilon_m = \frac{\Delta\omega_m}{\omega_m} = \mp \frac{\Delta N_r}{KN_m} \pm \frac{\Delta N_a}{N_m} \mp \frac{\Delta t_r}{t_r} \tag{3}$$

Thus, ϵ_m, defined as the maximum relative error, arises from three sources, the first two of which arise from displacements and the other, from time as follows:

(a) Error in determining the increment in number of relative cycles ΔN_r

(b) Error in determining the increment in number of cycles of antenna rotation ΔN_a

(c) Error in determining the increment in time Δt_r

The method of data reduction has been found to affect the magnitude of these three sources of error. For example, consider the following record-reduction methods:

Data-reduction method 1.- Briefly, method 1 consists of calculating the relative and antenna angular velocities separately and then obtaining the vehicle roll velocity from them as follows:

1. Read from record and tabulate:

(a) Relative-angular-displacement increments N_r, in whole numbers of cycles

(b) Corresponding time intervals t_r by interpolation

(c) Corresponding numbers of antenna revolutions N_a

(d) Total elapsed time to center of each displacement increment

2. Calculate the relative angular velocity ω_r for each set of readings by the equation

$$\omega_r = \frac{2\pi N_r}{t_r}$$

3. Calculate the corresponding values of the antenna angular-velocity by the equation

$$\omega_a = \frac{2\pi N_a}{t_r}$$

4. Obtain values of rate of roll, for plotting against elapsed time, by equation (2):

$$\omega_m = \omega_a - \frac{\omega_r}{2}$$

Data-reduction method 2.- Method 2 consists of first obtaining the vehicle angular displacement from the relative and antenna displacements and then calculating the rate of roll. The displacement determination is made so that antenna displacement is an absolute quantity with negligible error. The steps to be followed in this method are as follows:

1. Read from record and tabulate:

   (a) Numbers of antenna revolutions N_a in whole numbers of cycles

   (b) Corresponding numbers of relative cycles N_r by interpolation

   (c) Corresponding time intervals t_r by interpolation

   (d) Total elapsed time to center of each displacement increment

2. Determine the roll displacement increments by the relation

$$N_m = N_a - \frac{N_r}{2}$$

3. Obtain values of rate of roll, for plotting against elapsed time, by the equation

$$\omega_m = \frac{2\pi N_m}{t_r}$$

Comparison of methods 1 and 2.- For comparison of these two methods, careful examinations of an actual record were made and the absolute errors estimated as shown in the following table:

Reduction method	ΔN_r (cycles)	ΔN_a (cycles)	Δt_r (sec)
1	1/25	1/45	0.0005
2	3/50	Negligible	.0005

The quantity ΔN_r shows an increase in method 2 over method 1 primarily due to the necessity of interpolating between cycles. In both methods, 1/50 of a cycle is the quantity assigned to the uncertainty of determining the position of a peak in the relative roll signal. The absolute error ΔN_a is introduced by interpolation between pips, in method 1, which becomes negligible in the second method if reasonable care is taken. These values are for a particular set of conditions and are given for comparison purposes only. They are dependent somewhat upon ω_r and recording film speed.

By use of the quantities in the table and equation (3), the errors of the two methods of reduction are compared in figure 7 for a constant time interval of 0.1 second. (In practice, this time interval should be as large as possible consistent with angular acceleration.) These curves show good correlation with results obtained from the work up of actual records. They are correct for both positive and negative directions of missile rotation and no ambiguity exists provided the antenna rotational frequency is always greater than the missile rolling frequency.

DISCUSSION

Equation (3) suggests several methods for improving the rate-of-roll data secured, as the quantities which are controllable, K, ω_r, and ω_a, may possibly be varied in such a manner that the total error is minimized.

When the vehicle is rolling at an extremely low rate, it is necessary to rotate the antenna at such speed that the instantaneous roll velocity is secured more frequently than twice per revolution. The minimum antenna rotation velocity is determined then by the angular accelerations of the vehicle at low rolling velocity. As indicated in equation (3), however, increasing antenna velocity to greater and greater

values has little or no effect on the attainable accuracy. One method of eliminating ΔN_a errors consists in driving the antenna with a synchronous power supply in which case errors in determining antenna speed can be made negligible.

If K is made very large by electronic multiplication of the relative roll signal, the first term in equation (3) becomes correspondingly small. It is feasible then to increase K until the error in reading portions of a cycle ΔN_r becomes inversely proportional to the relative roll frequency as a result of limitations in recording film speeds. Larger values of K will not, then, result in any further increase in accuracy unless the recorded relative frequency is decreased by electronic subtraction of a multiple of the antenna rotational frequency.

A method of further increasing over-all accuracy and reducing work-up time is to perform all the required subtractions and differentiations electronically. It is possible to select antenna rotational speeds and multiplier ratios such that the frequency corresponding to a given rate of roll appears as a frequency deviation, say within ±1000 cycles per second, on a carrier frequency between 100 kilocycles and 200 kilocycles. This signal can then be electronically analyzed for frequency deviation by a frequency discriminator. The final result will be a direct current, which is proportional to the frequency deviation, capable of being recorded on a galvanometer type of oscillograph recorder.

Thus, the final subtraction of the remaining carrier is accomplished simultaneously with electronic differentiation of roll displacement. The galvanometer deflection from a reference, then, will be directly proportional to rolling velocity. By recording this deflection on a suitable strip chart with appropriate timing marks, a time history of the instantaneous values of rolling velocity will be obtained. Recent developments have indicated that this approach is practicable.

Langley Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Air Force Base, Va., November 14, 1949

REFERENCE

1. Van Allen, J. A.: Loss of Spin of Projectiles. Part I - Experimental Method. Jour. Aero. Sci., vol 15, no. 1, Jan. 1948, pp. 35-38.

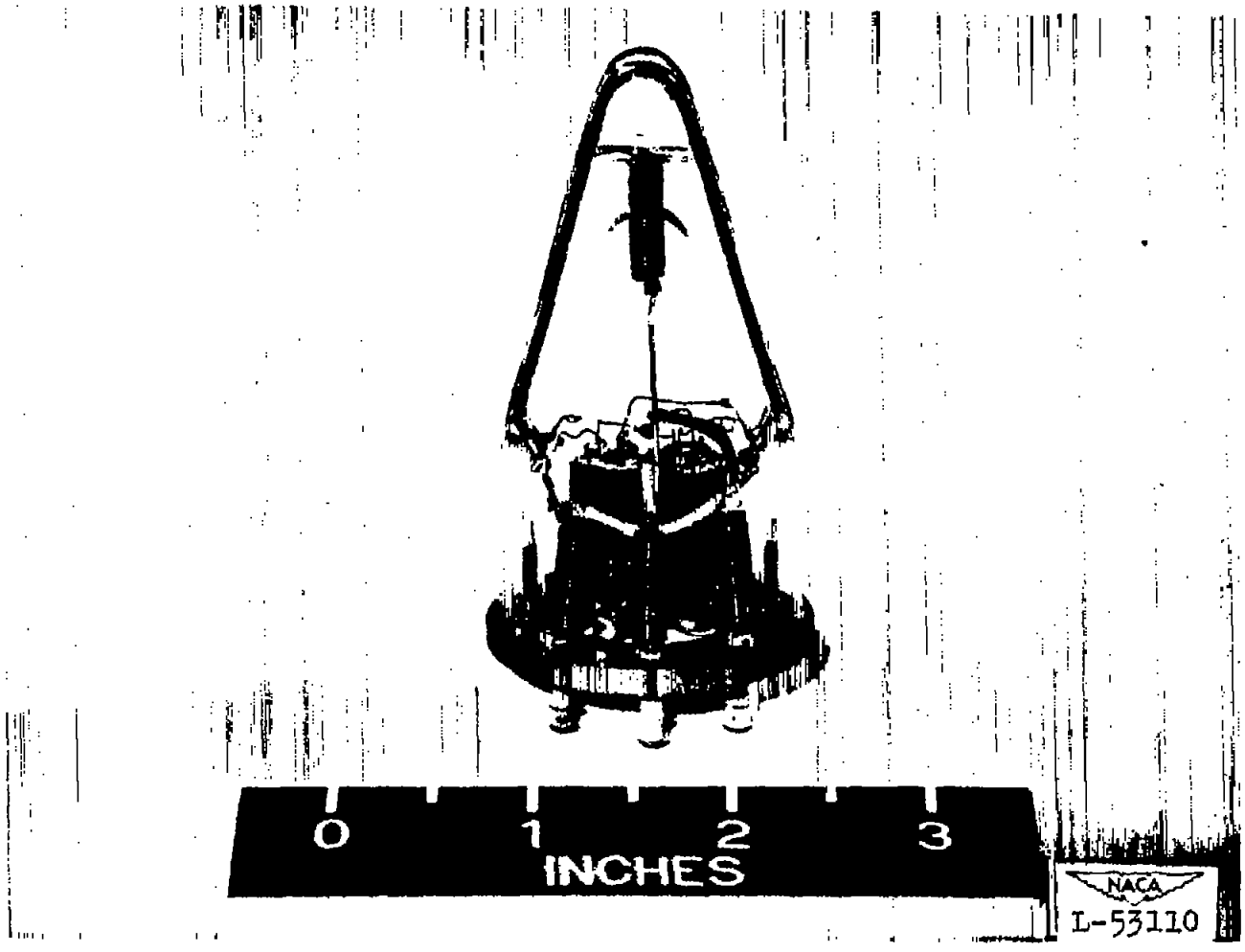

Figure 1.- Modified spinsonde transmitter.

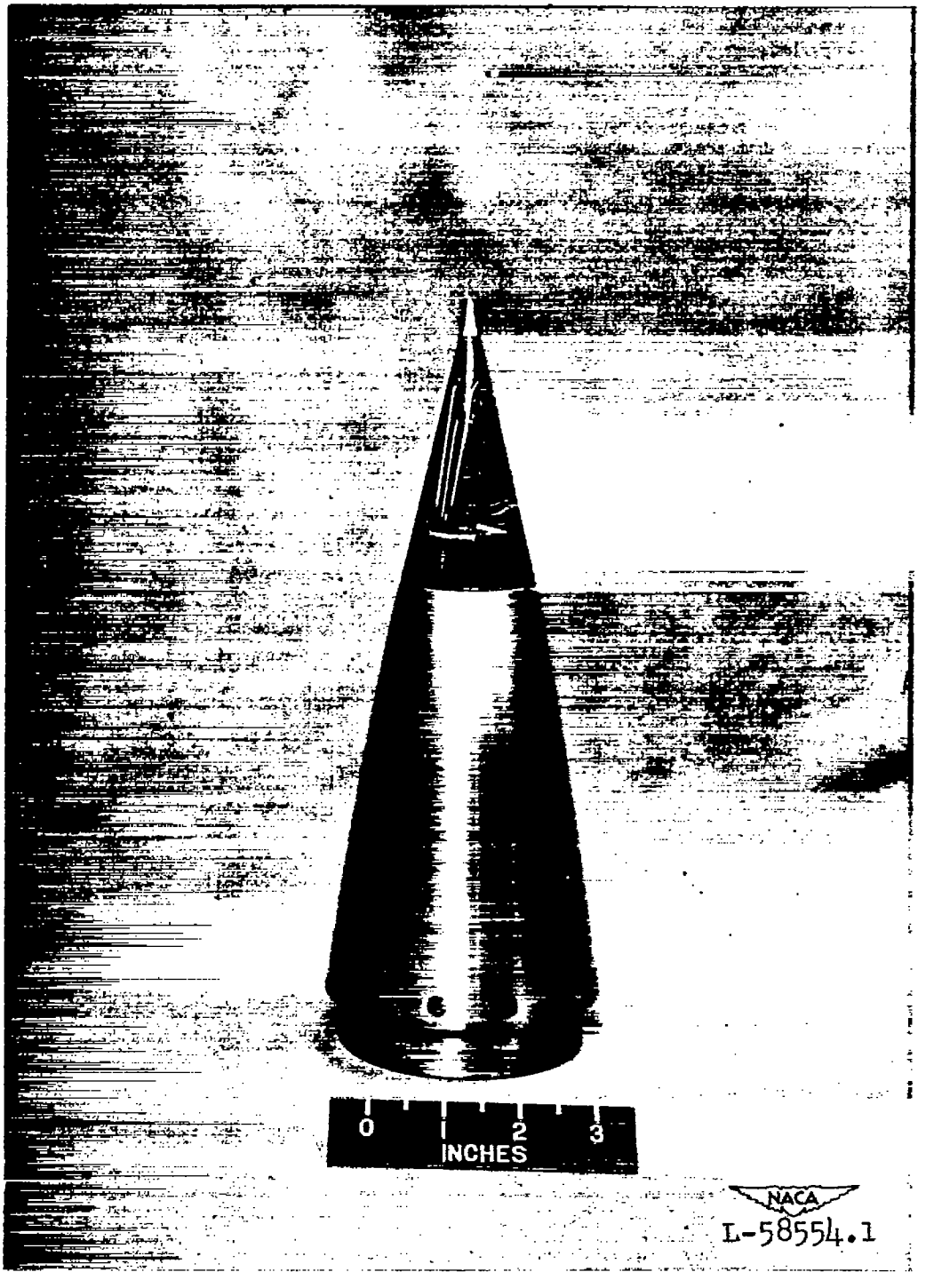

Figure 2.– Typical sonde installation.

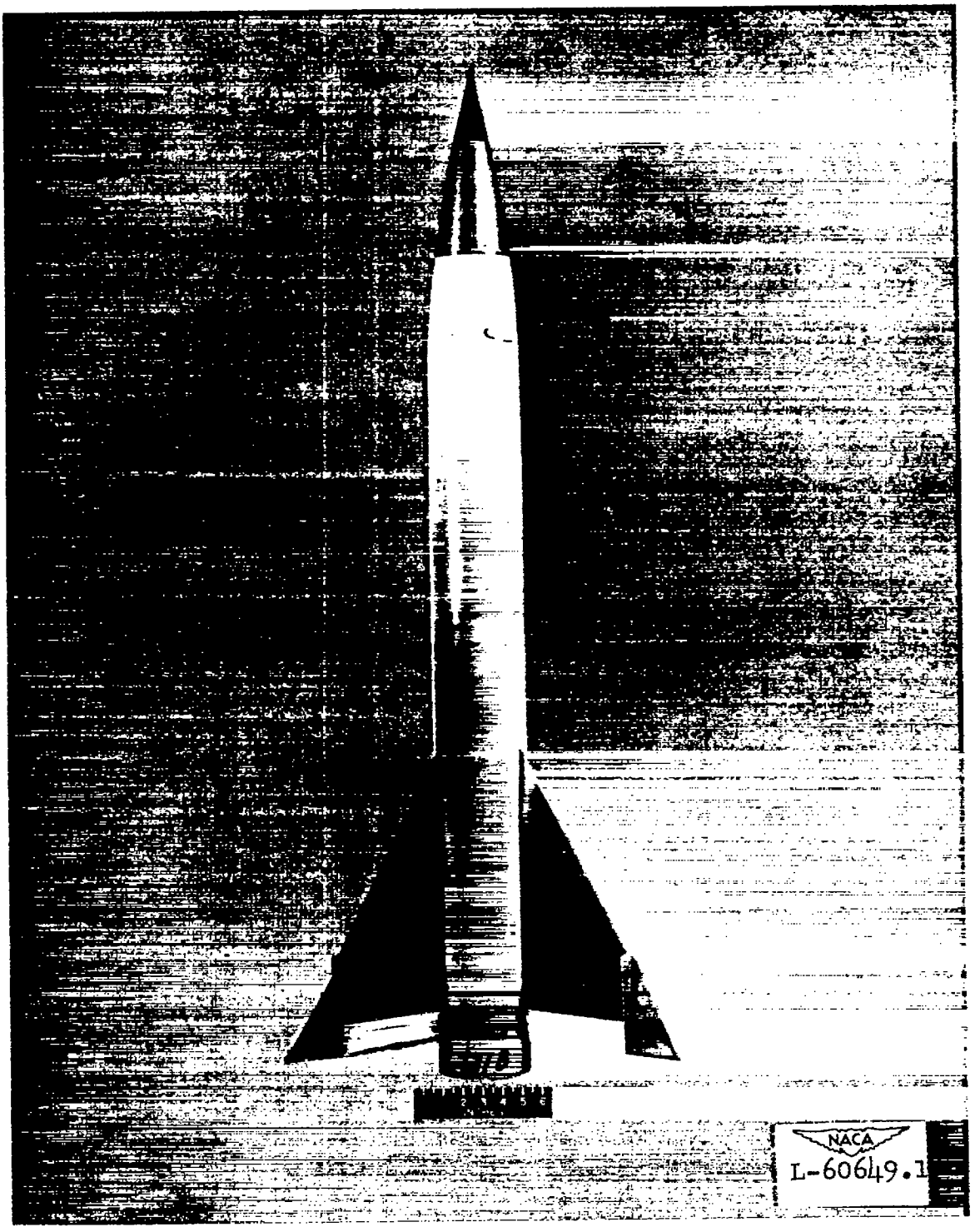

Figure 3.– Typical free-flight test vehicle.

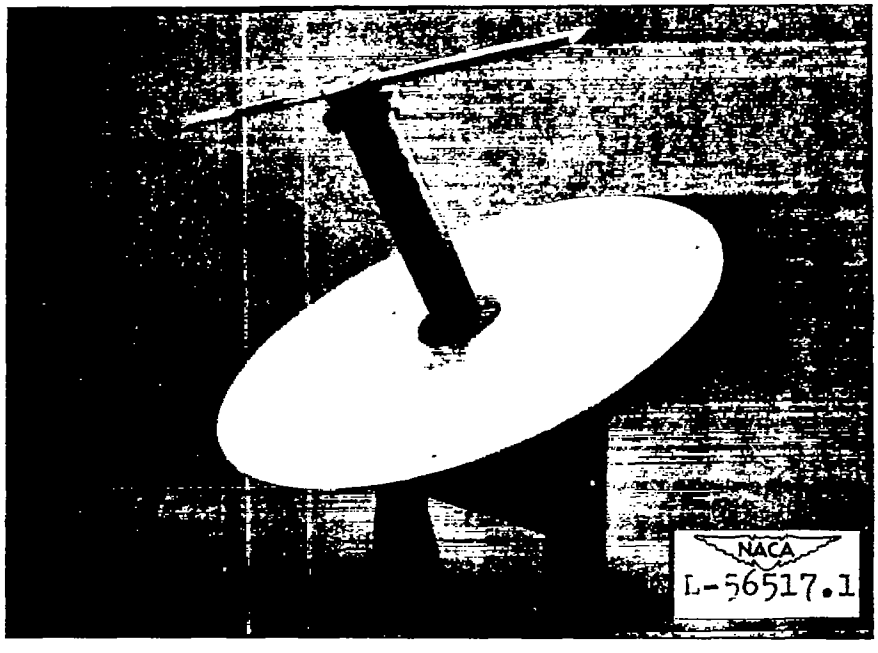

Figure 4.- Rotating antenna.

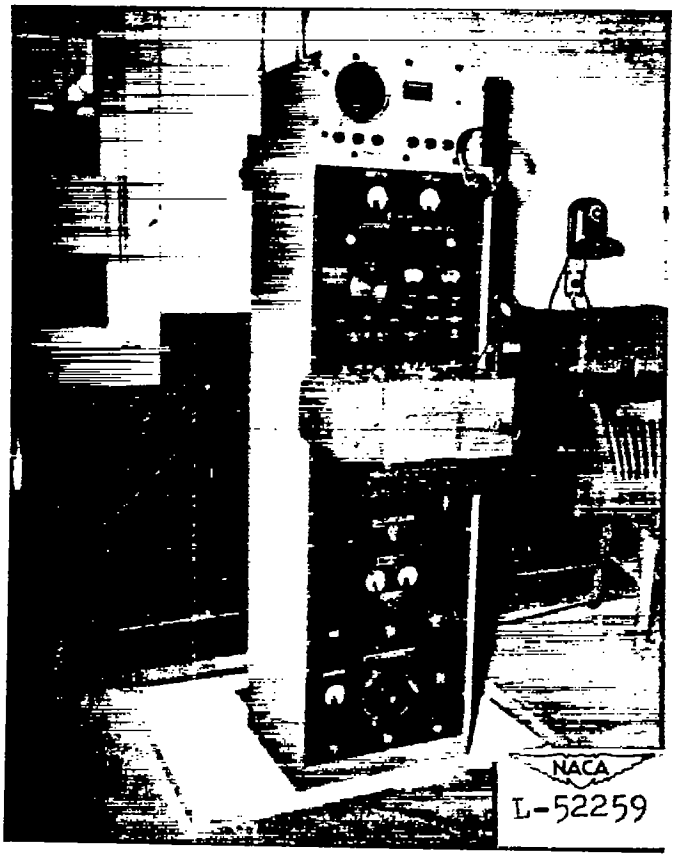

Figure 5.– Receiving station and recorder.

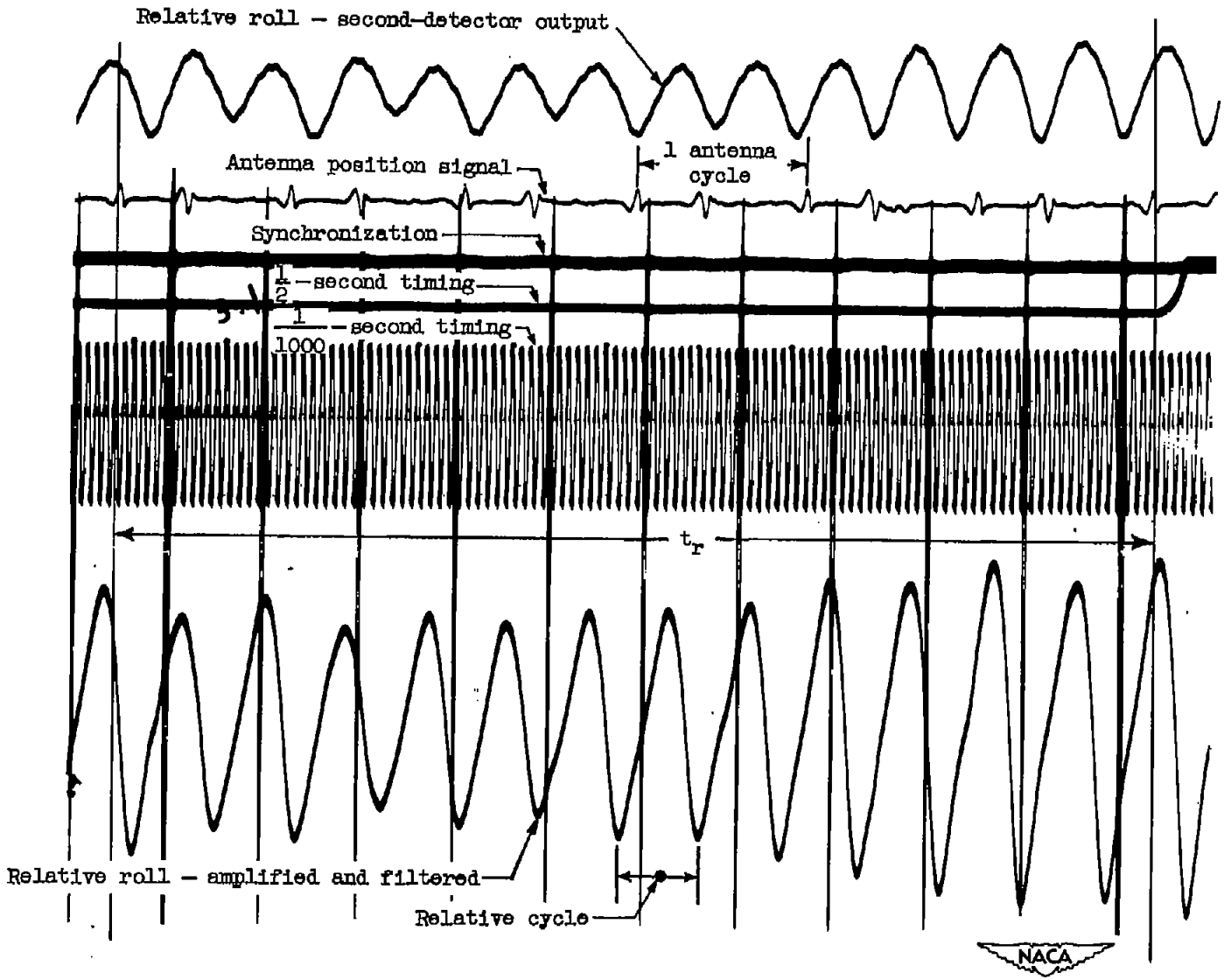

Figure 6.– Part of sample record from rate-of-roll test.

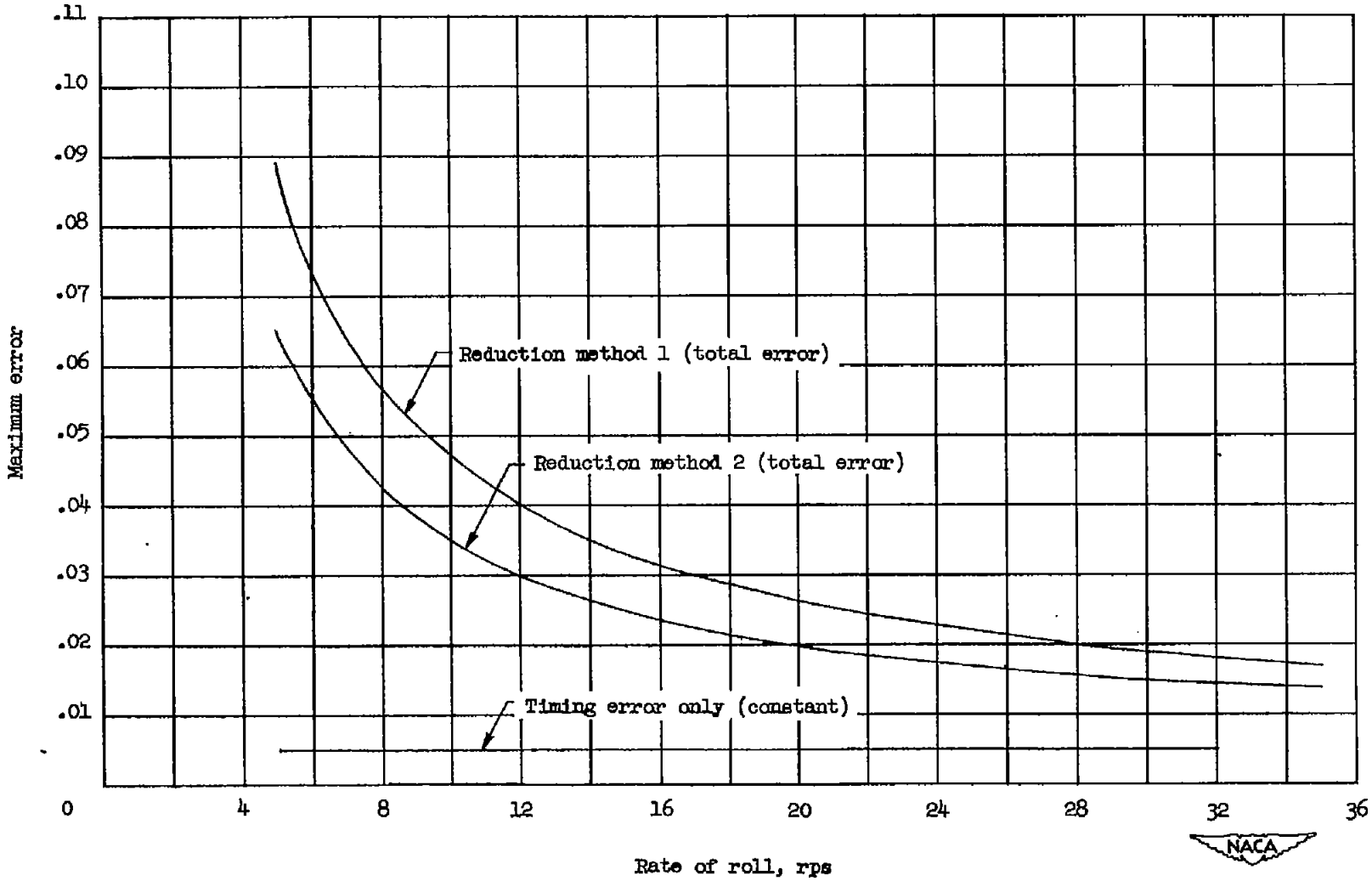

Figure 7.– Maximum error against rate of roll for time interval of 0.1 second.

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