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MEASUREMENT PLAN FOR THE CALIBRATION OF THE FAA/NAFEC AIRCRAFT

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1. INTRODUCTION AND BACKGROUND

The basic reason for these measurements is to obtain a calibration constant for the Federal Aviation Administration's (FAA) flight inspection aircraft (a Convair 580). This aircraft is equipped for various purposes, and among its equipment is a spectrum analyzer/data recording system. It is this system with its antenna that must be calibrated. For a given received signal level, it is desired to know what the field strength is external to the aircraft.

In order to do this seemingly simple calibration, a known field strength is needed and can be obtained by calibrating a non-directional beacon (NDB). This too may sound relatively simple, but it is not. The unknowns must be minimized so that the errors will be minimized. The ideal beacon would be on a perfectly flat, homogeneous earth and have an antenna that produces an ideal, circularly symmetric pattern. An ideal beacon, of course, is not available; so one (or more) that comes as close as reasonable must be found.

These measurements are a prelude to the measurement of the radiation of rf energy from power lines by power line carrier (PLC) communication systems. This measurement, too, is a part of a larger effort to assess the potential for PLC systems to interfere with automatic direction finder (ADF) radio compasses.

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The calibration and the PLC radiation measurement flights and data collection are the responsibility of the FAA and the National Aviation Facilities Experimental Center (NAFEC). The data will be supplied to the Institute for Telecommunication Sciences (ITS) in the form described by this and subsequent measurement plans. ITS is responsible for any further data reduction and the PLC/ADF interference assessment study.

2. NON-DIRECTIONAL BEACON CALIBRATION

2.1 The Beacons

Two or three non-directional beacons, located on relatively flat and homogeneous ground, must be found. These NDB's should be of different frequencies, preferably widely separated in the 200 to 400 kHz band. As a part of the homogeneity requirement, due consideration must be given to the beacon being in an area clear of man-made conductive obstructions, such as railroads, power lines and pipelines. Lastly, the NDB antenna should be as near to circularly symmetric as is reasonable.

2.2 Ground-Level Field Strength Measurements

Ground-level measurements are used to determine the ground conductivity and to provide a scale factor for the field-strength calculations described in the next section (2.3). The important beacon features described in the last section also are mathematical assumptions made in the next section.

The ground-level field strength is to be measured along two radials of each beacon. Five to ten values of the field strength are needed along each of the two radials in the range of 1 to 10 km. It is important to know the distance from the beacon to each measurement point accurately; therefore the radials and each measurement point must be carefully chosen and recorded. The U.S. Geological Survey topographic maps of the 7-1/2' or 15' series are excellent for this work.

Ideally, the aircraft calibration (described in Sec. 3) should be performed at the same time as the ground-level measurements to ensure that the radiated power is the same for both measurements and that the ground conductivity has not changed appreciably (due to moisture content). If this simultaneous measurement is not feasible, then a way of observing the radiated power must be used. A "close-in" field strength measurement would be very effective. Also, the weather conditions prior to and during the ground-level measurements should be recorded, and the aircraft calibration measurements should not be made if it is felt that the moisture content has changed significantly.

2.3 Field Intensity and Structure at Non-Zero Heights

In general, the electromagnetic field radiated from a short, vertical antenna located on a smooth plane earth is vertically polarized. The field strength is [Wait, 1964]

$$E(d) = \frac{9.487\sqrt{P}}{d} A(z) \quad , \qquad V/m \tag{1}$$

where P is the effective radiated power in watts and A(z) is the flat earth attenuation function. The geometrical parameters used are defined in Figure 1.

$$A(z) = \left(1 - R_o \delta \, e^{z^2} \operatorname{erfc}(z)\right) \quad , \tag{2}$$

where δ is the surface impedance of the ground,

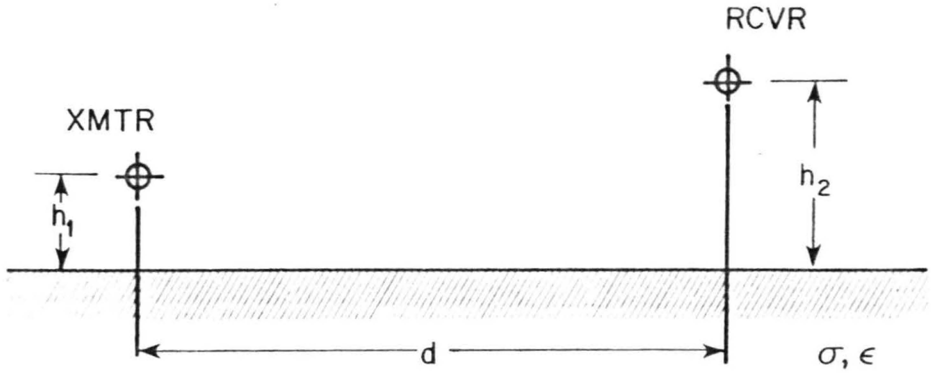

Figure 1. Geometric parameters used to calculate the non-directional beacon field strength.

$$\delta = \begin{cases} \sqrt{\eta - 1} \;/\eta & \text{for vertical polarization} \quad , \\ \sqrt{\eta - 1} & \text{for horizontal polarization} \quad , \end{cases} \tag{3}$$

and

$$\eta = \varepsilon - i \, \frac{1.8(10)^7 \, \sigma}{f} \quad , \tag{4}$$

where σ is the ground conductivity in mhos/m (siemens/m), ε is the permittivity of the ground relative to that of free space, and f is the radio frequency in kilohertz.

$$R_o = e^{i\pi/4} \sqrt{\pi k D/2} \quad , \tag{5}$$

$$D = \sqrt{d^2 + (h_1 - h_2)^2} \quad , \tag{6}$$

$k = 2\pi/\lambda = 2\pi f/c$, where $\lambda = f/c$ is the free space wavelength,

$$z = e^{i\pi/4} \sqrt{\frac{kD}{2}} \, \delta \left(1 + \frac{h_1 + h_2}{\delta D} \right) \quad , \tag{7}$$

and erfc (z) is the complementary error function [Abramowitz and Stegun, 1964].

Inspection of equations (1) through (7) shows that the following parameters must be known:

Radio system parameters: radio frequency, f, and effective radiated power, P.

Geometrical parameters: antenna heights, h_1 and h_2, and path length, d.

Ground parameters: conductivity, σ, and relative dielectric constant, ε.

Since σ is the usually greater than 10^{-3} and ε is the order of 10, equation (4) shows that the exact value of ε is unimportant for frequencies less than 400 kHz - the value of η is controlled by the ground conductivity σ.

The antenna heights and path lengths are independent variables when calculating the field structure. The two remaining parameters, P and σ, can be determined from measurements made on the ground along a radial from the transmitter. The measured field strengths are plotted in decibels as a function of distance, and a straight line is fitted to the points. The slope of the line determines the ground conductivity, σ, and the value of the line at 1 km determines the radiated power P.

At distances sufficiently far from the transmitting antenna, the curvature of the earth must be taken into account. Then [Fock, 1965; Wait, 1964],

$$E = 9.487 \sqrt{P} \sqrt{\frac{v}{12 \sin}} \frac{e^{-i3\pi/4}}{a} \int_{\Gamma} e^{-ixt} F_I(q,t) \, dt \quad , \tag{8}$$

where a is the radius of the earth, $\Theta = d/a$,

$$v = (ka/2)^{1/3} \quad , \; x = v\Theta, \text{ and } q = -iv\delta \quad . \tag{9}$$

The contour Γ comes from $\infty \, e^{-i\pi/4}$ on a straight line with a slope of -1 to $(\mathrm{Re}(t_o) - i/2 \, \mathrm{Im}(t_o))$ and then proceeds on a straight line with slope +1 to $\infty \, e^{-i3\pi/4}$. t_o is the first pole of $F_I(q,t)$. Re designates the "real part of" and Im designates the "imaginary part of".

$$F_I(q,t) = \frac{H_1(h_1)\ H_2(h_2)}{\dfrac{W_1'(t)}{W_1(t)} - q} \quad . \tag{10}$$

The height gain functions are

$$H_1(h) = \frac{W_1(t - y)}{W_1(t)} \tag{11}$$

and

$$H_2(h) = -.5i \left\{W_2(t - y) \left[W_1'(t) - qW_1(t)\right] \right.$$

$$\left. -W_1(t - y)\left[W_2'(t) - qW_2(t)\right]\right\} \quad , \tag{12}$$

where $y = kh/v$. Note that $H_z(0) = H_2(0) = 1$. The functions $W_n(t)$ are Airy functions [Wait, 1964] which satisfy

$$W_n'(t) = tW_n(t) \quad . \tag{13}$$

The only parameter required to evaluate (8) that is not required for (1) is the radius of the earth, a, and this is known. Thus, (8) can be used to extrapolate measurements made near the transmitter to much greater distances, assuming that the ground conductivity does not change as we move away from the transmitter.

Well-established computer programs exist for evaluating equations (1) and (8) [Berry, 1978]. The computer programs have been validated by comparison with the standard CCIR curves [CCIR, 1970] and with Federal Communications Commission methods developed originally by Norton [1941].

3. AIRCRAFT CALIBRATION

3.1 System Description

The FAA's flight inspection aircraft is a Convair 580. Relative to the measurements described in this plan, it contains a spectrum analyzer/microprocessor data collection system. The ADF radio compass "sense" antenna is coupled to the spectrum analyzer input. The sense antenna is a "tee" type of antenna that is mounted on the belly of the aircraft. This antenna is composed of a relatively small vertical element and a larger horizontal top load.

The data collection system has a maximum sensitivity of -120 dBm and also can record the output of the inertial navigation system (INS). The latter feature is quite important to these measurements because the location of the aircraft must be known at all times during data collection. The cruising speed for the aircraft is 150 knots.

3.2 Flight Patterns

The patterns to be flown over the beacons during the data collection are of two types: radials and orbits. There are the same number of each, and for each radial there is an associated orbit. The signal level should be measured over the full circumference of the smaller orbits and segments of the larger orbits, and over that portion of the radial that includes the associated orbit. It is important to have data on the radial at the point it crosses the orbit. Successive orbits should be flown in opposite directions and successive radials flown alternately inbound and outbound. These flight paths are shown in Figure 2; they should be flown as accurately as possible. The arcs of the larger orbits over which data are to be taken should be no less than 30° and centered on the ground-level measurement directions. Two of the radials should be associated with one ground-level measurement direction and two with the other one. They should be flown at a bearing that is about 5° off the ground-level measurement radial.

3.3 Required Data

The signal level as measured by the spectrum analyzer in terms of voltage (or dBV or equivalent) or in terms of power (or dBm or equivalent) should be recorded at a sample rate of about 20 samples per second but not less than 10 per second. There is no reason to sample faster than 100 per second. The aircraft position (from the INS) should be recorded each second. The needed INS data are the latitude, longitude, elevation, and heading. A bandwidth of 100 Hz should be used with the spectrum analyzer in the "manual scan" mode. If this bandwidth is too narrow for tuning drift problems, a larger one may be used, and it will be necessary to have the beacon code ID turned off during the measurements so that the carrier is stable.

All pertinent information for each orbital or radial flight should be recorded in a logbook. This information should include:

- the operators;
- the time and date;
- weather conditions;
- sample rate and structure of the recorded data;
- spectrum analyzer settings; i.e. bandwidth, input attenuations, etc.;

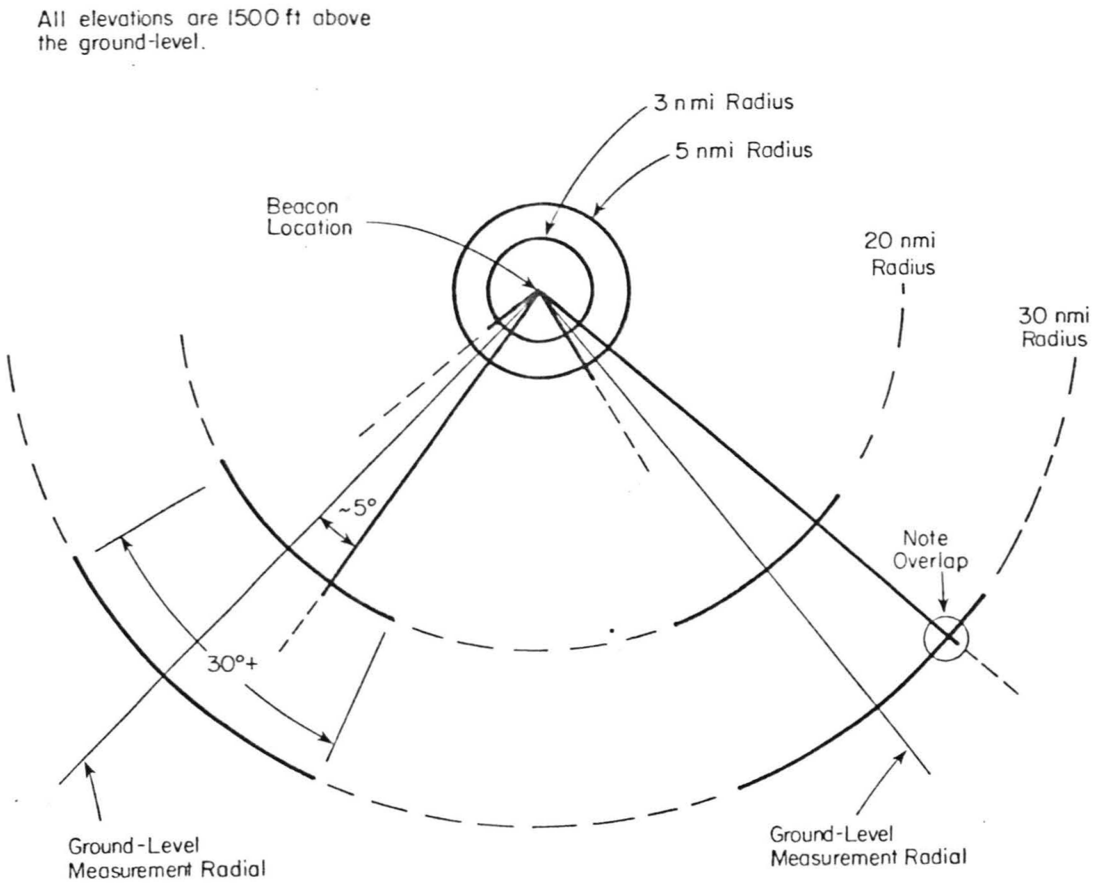

Figure 2. Flight paths for aircraft calibration. Data should be taken where solid, heavy lines are shown.

- the bearing of the radial or the radius of the orbit as determined manually using any of the navigation aids in the aircraft;
- a description of which records on the storage medium contain the data for this particular run;
- the bank angle of the aircraft for the smaller orbits; and
- any relevant or irrelevant ideas or thoughts that come to mind during the work.

In addition, the basic configuration of the receiving system should be recorded so that it can be configured the same way when the power line carrier measurements are made. All knob and front panel settings should be recorded.

3.4 Additional Data

The data described in this section may or may not be used to help arrive at the calibration constant, but are necessary to validate the required data and the procedures used.

The following describe the additional data needed:

- several calibration runs using a calibrated signal generator as a signal source connected both before and after the sense antenna "tee", using a wide range of signal levels;
- repeat one or more of the smaller orbits in the opposite direction;
- repeat one of the longer radials without the ADF receiver connected to the sense antenna "tee"; and
- make some noise measurements on an adjacent clear frequency at each beacon.

3.5 Data Format

The format chosen to transmit the data from NAFEC to the Institute should cause the least overall effort in data handling. The data should be delivered on 9-track tape at a density of either 800 or 1600 bpi. An ASCI "card image" coding would be the easiest to read. The tape format should be composed of fixed length records (e.g. 1024 bytes). Partially filled records may be "blank" filled. The data for each flight path should begin with "header data", giving the flight path, time of day, beacon name, etc. The data for each flight path should be terminated with an end-of-file (EOF) mark. The end of all data on a reel of tape should be delimited with two EOF's.

Figure 3 is a picture of the data structure on the tape.

4. DATA REDUCTION AND THE CALIBRATION CONSTANT

The calibration constant sought relates the field strength external to the aircraft (in volts/meter) to the received signal (in volts) at the input to the spectrum analyzer. If the signal level is recorded as a power, then a conversion to voltage could be made.

Let S represent the signal level in volts and E, the vertical electric field strength in volts/meter, then

$$E = C(f)\ S \quad , \tag{14}$$

where C(f) is the calibration constant. It will have units of meter^{-1}. Note that it is implied here that C(f) is a function of frequency, f; it also may be a function of the orientation of the aircraft and the signal level S.

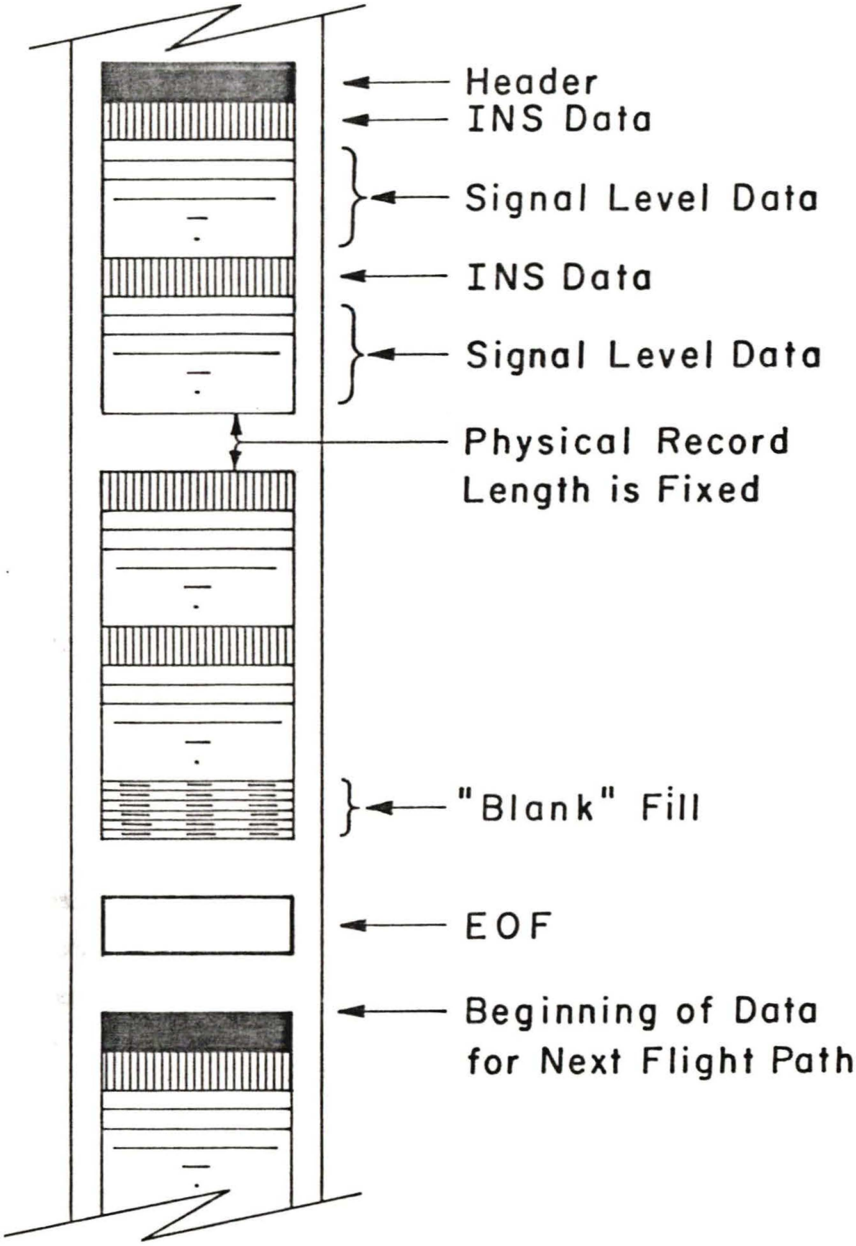

Figure 3. Structure and sequence of the data supplied on 9-track tape.

Equation (14) represents the way that C will be used to obtain the field strength given the signal level. The purpose of this work, however, is to obtain C; therefore

$$C(f) = E/S \quad . \tag{15}$$

The procedure is to (1) measure S and record location data, then (2) use the location data to calculate E using the prediction methods outlined in Section 2.3, and (3) calculate C(f).

Since C(f) may be a function of the aircraft orientation and, possibly, S, the data from each run (orbit or radial) will be reduced separately. From these data, then it should be clear if C is a function of S and to what extent it depends on the aircraft orientation.

5. REFERENCES

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