The AN/APN-81 Doppler Navigation System*

FRANK A. McMAHON†

Summary—**The AN/APN-81 is a self-contained Doppler navigation system which accurately determines ground speed and drift angle independently of ground aids. This paper explains the techniques employed in the measurement of ground speed and drift angle. The beam pattern is described and major system parameters are given. In block diagram form, the functions of the transmitter and receiver, the frequency tracker, and the wind computer are explained. Accuracies of measurement and some specific applications of the equipment are given.**

Introduction

ONE of the basic problems in navigation is the accurate computation of ground-speed and drift-angle information. Most of the techniques developed for this purpose have one or more disadvantages. Ground-based aids may be required; the device involved may require clear weather (for observation of the ground), may be inoperable over water, or may be inordinately heavy or complex in comparison with the accuracy achievable.

A new technique, utilizing the "Doppler" effect, has recently made it possible to produce a system of practical size and weight which determines an aircraft's ground speed and drift angle to a high degree of accuracy. The system operates automatically under any atmospheric conditions and over any type of terrain, including water.

General Precision Laboratory Incorporated, in cooperation with the Communication and Navigation Laboratory (now the Weapons Guidance Laboratory) of the Air Force Wright Air Development Center, has developed this system, called the AN/APN-81 Doppler Radar Navigation Set. See Fig. 1.

The APN-81 transmits rf energy to the ground and measures the shift in frequency (the "Doppler" shift) in the return energy in order to determine aircraft ground speed; through the use of a special beam configuration, drift angle is also determined.[1] These measurements are made continuously and directly. The APN-81 is contained entirely within the aircraft and is completely independent of ground-based aids. To operate the APN-81, it is only necessary for the operator to turn the power switch to the ON position.

The operational characteristics of the APN-81 are summarized in Table I, opposite. The weights and volumes of the boxes constituting the APN-81 are given in Table II. The receiver-transmitter and the two electronic control amplifiers are pressurized components. In addition, these boxes require cooling air, which is forced through internal air-to-air heat exchangers in the units. Power required to operate the APN-81 system is 100 watts dc at 28 v, 1200 watts three-phase 115 v ac, and 500 watts single-phase 115 v ac.

Fig. 1—AN/APN-81 Doppler radar system components.

Because of its high accuracy and its independence of ground-based aids, the APN-81 is of optimum utility in supplying accurate ground-speed and drift-angle data to navigational and similar type computers. Some specific interconnections are discussed below.

Antenna Pattern Considerations

In Fig. 2, a transmitter in the aircraft is directing rf energy toward the ground. The Doppler frequency shift in the return energy is given by:[2]

$$\Delta f = \frac{2V}{c} \cdot f_t \cdot \cos \gamma \tag{1}$$

* Manuscript received by PGANE, September 10, 1957.

† General Precision Laboratory Inc., Pleasantville, N. Y.

[1] F. B. Berger, "The nature of Doppler velocity measurement," IRE Trans., vol. ANE-4, pp. 103–112; September, 1957.

[2] W. R. Fried, "Principles and performance analysis of Doppler navigation systems," this issue, p. 176.

TABLE I

Operational Characteristics

	Limits of Operation Min.	Max.
Altitude, feet	500 (above terrain)	70,000
Ground Speed, knots	70	700
Acceleration without Signal Loss, G's		0.7
Drift Angle, degrees		
Right	0	49
Left	0	49
Heading, degrees	No limit	No limit
Wind Velocity, knots	0	240
Wind Direction, degrees	No limit	No limit
Aircraft Pitch without loss of signal, degrees		
Nose Up	0	24
Nose Down	0	14
Aircraft Roll without loss of signal, degrees		
Right wing down	0	15
Left wing down	0	15
Aircraft Pitch Rate, degrees/second	0	18
Aircraft Roll Rate, degrees/second	0	18
Aircraft Yaw Rate, degrees/second	0	18
Radiation frequency, mc	8700	8900

Accuracy Specifications

Ground Speed	± 2.1 knots (± 0.3 per cent of top speed) } averaged over 10 miles of travel.
Drift Angle	$\pm 0.15°$ } averaged over 10 miles of travel.
Wind Speed	± 3 knots or 2 per cent of wind speed, whichever is greater.
Wind Direction	Varies with wind speed. Typical extremes: $\pm 1.1°$ error at a wind speed of 215 knots; $\pm 12°$ at a speed of 13 knots.

TABLE II

Weights and Volumes, APN-81 Components

Nomenclature	Weight (pounds)	Dimensions (inches) $H \times W \times L$
Antenna AS-618A/APN-81	46	$12\frac{7}{8} \times 14\frac{3}{8} \times 28\frac{1}{2}$
Receiver-Transmitter, Radar RT-274A/APN-81 with Mounting MT-1216/APN-81	90	$16\frac{7}{8} \times 16\frac{1}{4} \times 23\frac{5}{8}$
Computer-Frequency Tracker CP-185/APN-81 with Mounting MT-1192/U	34	$9\frac{5}{8} \times 9\frac{1}{4} \times 18\frac{1}{4}$
Amplifier, Electronic Control AM-742/APN-81 with Mounting MT-1218/U	65	$13\frac{3}{8} \times 13\frac{1}{2} \times 23\frac{1}{2}$
Amplifier, Electronic Control AM-743/APN-81 with Mounting MT-1191/APN-81	$9\frac{3}{4}$	$7\frac{3}{4} \times 6\frac{1}{8} \times 10\frac{5}{8}$
Amplifier, Electronic Control AM-758A/APN-81 with Mounting MT-1216/APN-81	91	$16\frac{7}{8} \times 16\frac{1}{4} \times 23\frac{1}{8}$
Control, Vertical Gyro C-1160/APN-81 with Mounting MT-1219/APN-81	$8\frac{5}{8}$	$7\frac{1}{2} \times 7\frac{1}{2} \times 8\frac{1}{4}$
Slaving Control, Type N-1 Compass System	$3\frac{3}{4}$	$5\frac{1}{8} \times 4\frac{5}{8} \times 4\frac{3}{4}$
Coupler, Directional CU-323/APN-81	$\frac{1}{4}$	$2\frac{1}{2} \times 2\frac{1}{4} \times 5$
Control, Radar Set C-1416/APN-81	3	$6 \times 5\frac{3}{4} \times 5$
Interconnecting Box J-605/APN-81	2	$3\frac{1}{4} \times 3\frac{1}{4} \times 7$
Interconnecting Box J-607/APN-81 with Mounting MT-1405/APN-81	$24\frac{1}{2}$	$5\frac{7}{8} \times 11\frac{1}{16} \times 16\frac{1}{16}$
Interconnecting Box J-608/APN-81 with Mounting MT-1404/APN-81	$6\frac{3}{4}$	$4\frac{1}{4} \times 8\frac{1}{4} \times 10\frac{7}{8}$

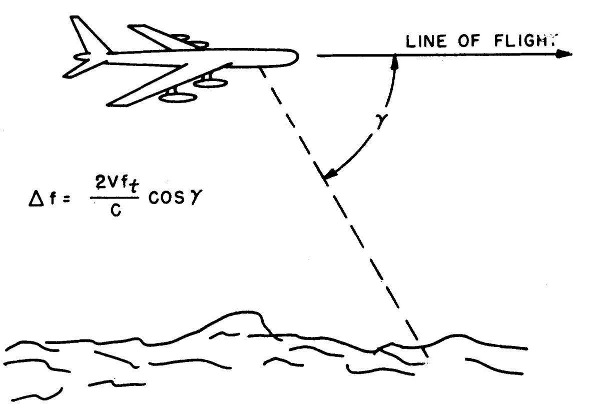

Fig. 2—Basic Doppler equation.

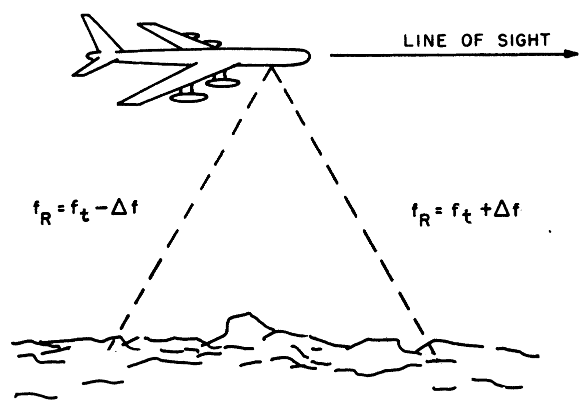

Fig. 3—Janus system.

where

Δf = Doppler frequency shift,

V = aircraft's ground speed,

c = speed of propagation of rf energy,

f_t = transmitted frequency,

γ = "looking" angle—(angle from line of flight to direction of beam).

From this equation, it is evident that the Doppler shift is essentially a function of the aircraft's ground speed. Use of a single beam, as shown in Fig. 2, has the disadvantage that the transmitter frequency must be "remembered" until the returned energy is received at the aircraft; this requires the use of an extremely stable transmitter or of a coherent oscillator whose frequency is locked to each transmitter pulse.[3] In the APN-81, a "Janus" system is used; this technique involves the use of two beams for computation of ground speed, one directed forward and one rearward (Fig. 3). The energy returned from the forward beam is of frequency $(f_t + \Delta f)$, and the energy returned from the rearward beam is of frequency $(f_t - \Delta f)$. By heterodyning the returned energies, Δf can be obtained independently of f_t.

When the Janus technique is used, there is an additional advantage in that the antenna stabilization need not be extremely accurate. For example, it can be shown that, when this method is used, an error of 1° in the

[3] F. B. Berger, "The design of airborne Doppler velocity measuring systems," this issue, p. 157.

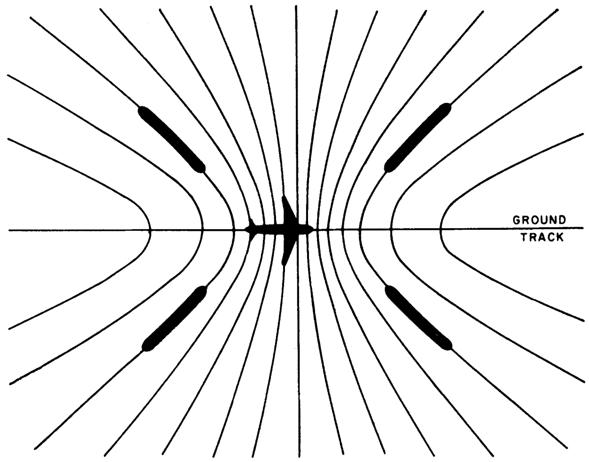

Fig. 4—Illumination pattern (antenna astride ground track, drift angle zero).

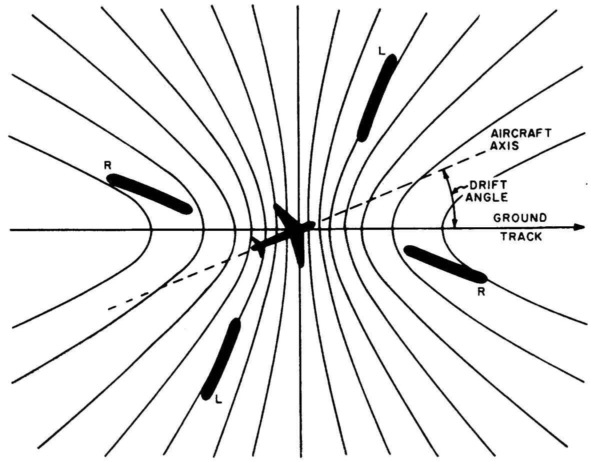

Fig. 5—Illumination pattern (antenna not astride ground track, drift angle not zero).

vertical causes only about 14 thousandths of a per cent error in measurement of ground speed.

The drift-sensing elements of the APN-81 utilize two pairs of beams, as shown in Fig. 4. The right front and left rear lobes are transmitted together and constitute the *right* beam. The left front and right rear lobes are transmitted together and constitute the *left* beam. Energy is transmitted to the right and left beams alternately at 1 cps.

All energy reflected from the ground at an angle γ undergoes the same Doppler frequency shift Δf, as can be seen from the basic Doppler equation (1). Consider the intersection with the ground of families of beams having constant γ angles. These intersections are hyperbolas, as shown in Fig. 4, and can be thought of as contours of equal Doppler frequency shift.

If the antenna is astride ground track, as in Fig. 4, the Doppler frequency shift in the left beam is equal to the Doppler frequency shift in the right beam.

If the antenna were off ground track (to the left, let us say, as in Fig. 5), the return from the left beam would indicate a lower frequency than the return from the right beam (note that the left front and right rear beams would be closer to the zero frequency shift line). The drift-computing elements sense this difference in frequency shift and utilize it as an error signal to servo the antenna to ground track. When the antenna is on ground track, the returns from the right and left beams exhibit equal frequency shifts; at this point, the error signal to the servo is zero, and the antenna is held on ground track. The angle (relative to the aircraft's longitudinal axis) through which the antenna has been turned to align it with ground track is equal to the drift angle.

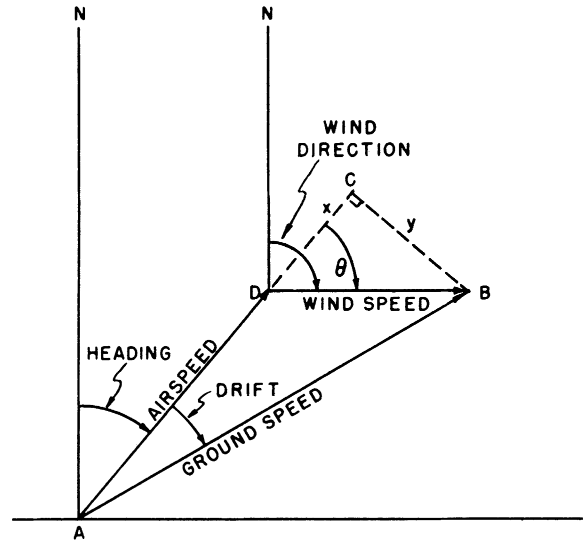

Fig. 6—The wind triangle.

Each beam of the antenna pattern is $3\frac{1}{2}°$ wide (at the half-power points) in the narrow (γ) direction, and 35° wide in the longer direction (see Figs. 2 and 4). Because of the 35° beamwidth, portions of the return energy from any one of the four segments do not all return at the same time. Thus, in passing over hilly terrain, the possibility of losing coherence between the front and rear beams (by having all energy of either beam return at a different time from the energy of the other beam) is diminished.

Memory Operation

When the reflected rf energy is of sufficient power and of appropriate characteristics, the computations of ground speed and drift angle are made in the APN-81 directly from the ground return, as explained in the preceding paragraphs. When the APN-81 is operating in this fashion, it is said to be in the *normal* mode. Under certain conditions, the signal-to-noise ratio in the reflected rf energy may be such that these computations cannot be made. It is desirable for the APN-81 to deliver ground-speed and drift-angle values even during these relatively infrequent periods of inadequate radar return. For this reason, the drift-angle and ground-speed values are used during the normal mode (in conjunction with automatic airspeed and heading inputs) to compute wind speed and wind direction continuously (see Fig. 6).

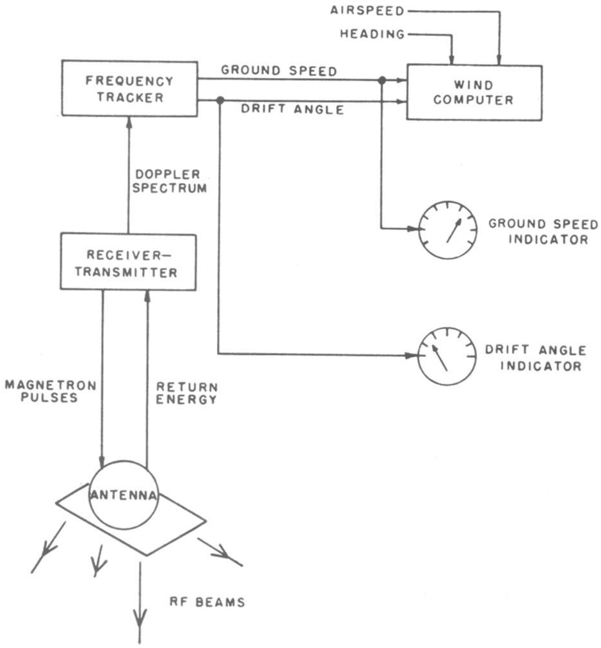

Fig. 7—Simplified system block diagram.

When the reflected rf energy cannot be used to compute ground speed and drift angle, the system automatically switches to a memory mode of operation; the previously computed wind speed and wind direction are "remembered" and are combined with air speed and heading inputs to compute ground speed and drift angle. If the condition of the reflected signal becomes satisfactory during the memory mode of operation, an acquisition circuit causes the equipment to return to the *normal* mode.

Conditions under which the system may go into memory include: 1) periods in which the operator turns off the transmitter by placing the radar silence switch on the C-1416 in the *silent* position; 2) the turn-on period, before a signal has been acquired; 3) operation over glassy smooth (Beaufort 0) seas;[2,4–6] 4) operation over extremely hilly terrain, when coherence is lost despite the broad antenna beams; 5) periods in which signal is lost because of aircraft maneuvering beyond the antenna limits of operation. *Memory* operation ordinarily represents a very minor portion of system operating time during a normal mission.

General System Description

Fig. 7 is a simplified over-all functional diagram of the APN-81 system. System functions are considered in this figure without regard to physical packaging of components.

[4] J. C. Wiltse, S. P. Schlesinger, and C. M. Johnson, "Backscattering characteristics of the sea in the region from 10 to 50 kmc," Proc. IRE, vol. 45, pp. 220–228; February, 1957.

[5] D. E. Kerr (ed.), "Propagation of Short Radio Waves," M.I.T. Rad. Lab. Ser., McGraw-Hill Book Co., Inc., New York, N. Y., vol. 13; 1951. See H. Goldstein, "Sea Echo."

[6] H. Davies and G.G. Macfarlane, "Radar echoes from the sea surface at centimeter wavelengths," *Proc. Phys. Soc.*, vol. 58, pp. 717-729; November, 1946.

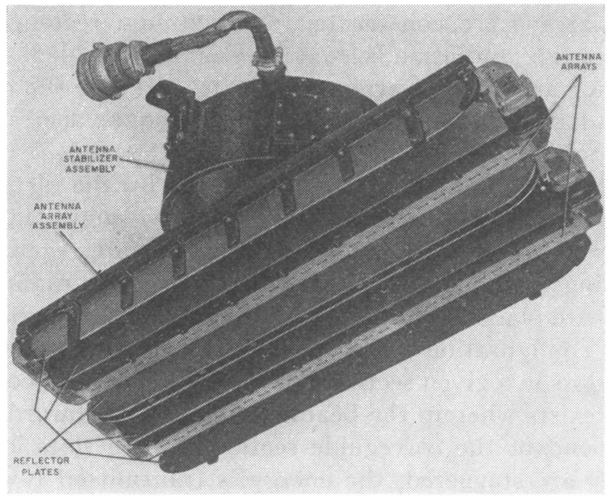

Fig. 8—Antenna array and stabilizer assembly.

The pulses of rf energy originate in the transmitter and are conveyed by waveguide to the antenna array assembly. The antenna arrays are stabilized in pitch and roll (not shown in Fig. 7).

The return pulses are applied to the receiver, whose function is to develop an output signal proportional to the Doppler frequency. As will be shown later, the output of the receiver is a wide band of noise (0 to 19.5 kc) on which is imposed a narrow spectrum of frequencies whose center is the desired Doppler frequency.

The frequency tracker measures this center frequency, and transmits it to an indicator as a ground speed reading in knots.[2] In conjunction with the antenna azimuth servo, the frequency tracker also computes drift angle. The latter is transmitted to an indicator as a direct reading in degrees.

The wind computer functions to compute wind speed and wind direction in the *normal* mode of operation. In the *memory* modes, ground speed and drift angle are computed in the wind computer from remembered values of wind speed and wind direction. Heading and air-speed inputs are required to enable the wind computer to perform its functions.

The Antenna

Fig. 8 shows the antenna array assembly and antenna stabilizer. The stabilizer contains the roll, pitch, and drift motors and gearing, in addition to rotary waveguide joints required to permit transmission of the rf energy from the receiver-transmitter to the arrays. Antenna travel is limited to $\pm 49°$ in drift, $\pm 15°$ in roll, and 14° nose down and 24° nose up in pitch. The roll and pitch motors in the stabilizer are controlled by separate roll and pitch stabilization signals provided (through amplifiers in the AM-758) by the vertical gyro C-1160. The gyro erection circuits are contained in amplifier AM-743.

The antenna array assembly contains four arrays, reflector plates, and a waveguide switch which effects the 1-cps left-right beam switching described previously.

The arrays are constructed of aluminum rectangular waveguide; radiation is from 27 resonant dumbbell slots in each array. Each array constitutes the axis of a cone of radiation, and the reflector plates confine the radiation to the desired pattern (see Fig. 4).

The looking angle, γ, is determined by the distance between radiating slots in terms of wavelength; in the APN-81, the looking angle is 69°. To obtain rearward-looking as well as forward-looking arrays, the radiating slots are placed differently with respect to the magnetic field configuration in the waveguide. By placing all of the slots in a given section of waveguide in line, a condition exists wherein the beam is transmitted toward the rear end of the waveguide section. Where slots in an array are staggered, the energy is transmitted toward the forward end of the waveguide section.

The Doppler Spectrum

Since the beam cannot be made of zero width, it overlaps a number of equal-frequency shift lines in the narrow direction (Fig. 4). Hence the Doppler return consists of a spectrum of frequencies, rather than a discrete frequency.[2,3] The Doppler shift which the APN-81 must compute is the center frequency of this spectrum. Since the illumination of the target surface is most intense at the center of the transmitted beam and diminishes in power toward the edges, the result is a spectrum whose amplitude is essentially Gaussian (normal) in distribution (see Fig. 9).

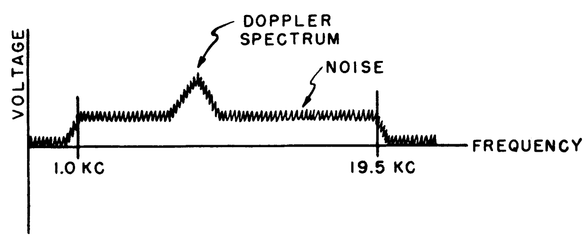

Fig. 9—Receiver output (idealized).

Consider a microwave signal transmitted from the antenna and incident upon some small physical object. The object scatters a portion of the incident signal in every direction, including the direction back toward the transmitter. The intensity of the back-scattered signal depends on the size, shape, orientation, and electrical properties of the scatterer.

In actuality, the reflector involved is not a single scatterer; a reasonably large area of the ground or of the surface of the sea is illuminated by the transmitted rf energy. Thus the target contains a large number of randomly positioned physically independent scattering centers. The net return signal available is then the sum of a large number of waveforms reflected by many scatterers. Each constituent waveform has an amplitude and a phase determined by the corresponding scattering center in the target area. Since these amplitudes and phases are randomly distributed quantities, the return signal can be adequately described only in statistical terms. The Doppler spectrum is statistically equivalent to narrow-band noise, with the band center frequency being the desired mean Doppler frequency.

The Receiver-Transmitter

The RT-274A/APN-81 contains all of the transmitter and receiver circuitry.

The transmitter uses an RK-6248 magnetron, tunable from 8700 to 8900 mc, and pulsed at an average of 50 kc (see Fig. 10). The pulse repetition frequency is modulated at a 63-cps rate to decrease the loss in returned energy caused by altitude holes. The output of the prf 50-kc blocking oscillator is a 0.9-μsec pulse (adjustable from 0.8 μsec to 1 μsec) applied to the 4PR60A modulator tube. The relatively high prf is required in order to make it possible to determine the Doppler frequency unambiguously. Audio research studies have shown that for this purpose it is necessary to examine at least two samples of return energy per cycle. With a maximum design speed of 700 knots (about 16-kc Doppler frequency), a prf of at least 32 kc is required. Safety factors dictate the nominal 50-kc figure. A secondary output of the prf oscillator is applied to a pulse stretcher, producing a 3-μsec negative gate for the receiver.

The high voltage power supply utilizes 35T tubes as rectifiers, and produces 4.1 kv ($\pm$300 v) at 52 ma.

Peak power output of the magnetron is 1100 watts (nominal), with an average power of 50 watts (nominal). The duty cycle is therefore $4\frac{1}{2}$ per cent (nominal).

Fig. 11 shows the receiver elements. The frequencies of the rf returns from the forward and rearward arrays are $f_t+\Delta f$ and $f_t-\Delta f$, respectively. These signals are fed through waveguide to the magic tee duplexer, where mixing with the 2K25 klystron local oscillator output occurs in a balanced mixer utilizing 1N23C crystals. The mixer produces frequencies of (30 mc$+\Delta f$) and (30 mc$-\Delta f$), which are fed to the IF amplifier. The duplexer contains a 1B63A tr tube and a 1B37 atr. The klystron is tunable manually by means of a knob on the front panel of the receiver-transmitter unit. When manual (coarse) tuning has been accomplished, an automatic frequency control circuit keeps the local oscillator frequency 30 mc below the magnetron frequency. The afc circuit consists of a 1N23C crystal to heterodyne the magnetron and local oscillator frequencies, a wide-band (3-mc bandwidth) IF amplifier, a modified Foster-Seely discriminator, and a phantastron output. The latter controls the klystron repeller plate voltage to maintain afc.

The outputs of the duplexer crystals are inputs to an IF amplifier having a 1.2-mc bandwidth. The input signals are fed to a balanced transformer; this serves to cancel local oscillator noise. The first IF stage consists of two triode-wired pentodes connected as a cascode amplifier with the advantage of low noise and high gain. The remaining three stages are high-gain pentode am-

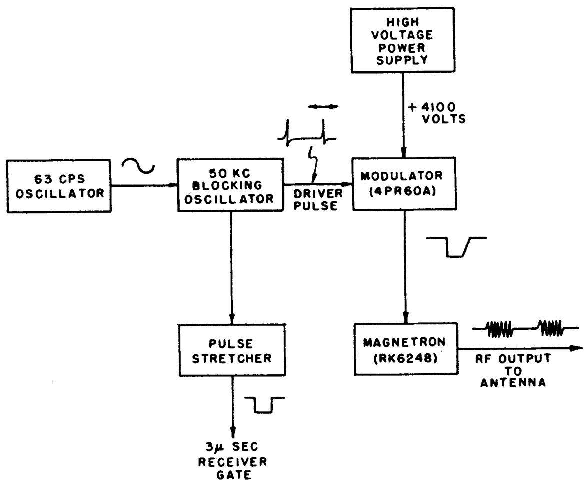

Fig. 10—Transmitter block diagram.

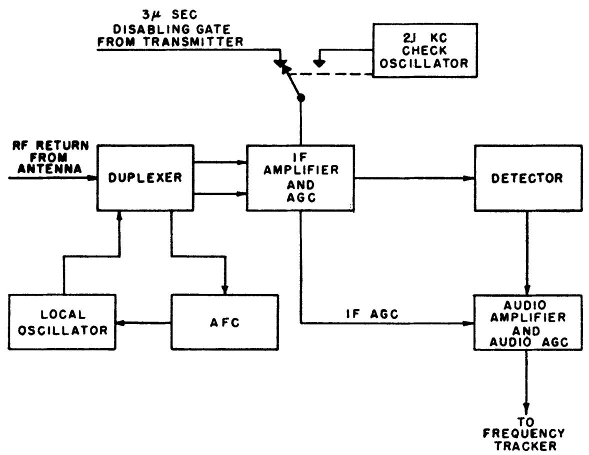

Fig. 11—Receiver block diagram.

plifiers. IF noise generated is about 1.5 db.

Automatic gain control is provided to restrict the IF output signal to about 1 volt in amplitude. The IF signal is detected, amplified, and filtered to provide a negative voltage proportional to signal level. This voltage is applied to the first three IF stages.

The negative gate generated in the transmitter circuits disables the IF amplifier while the magnetron is oscillating. In order to monitor system operation, a 2.1-kc oscillator signal can be applied (by operating the system monitor switch on control panel C-1416) in place of the receiver gate. This has the effect of amplitude modulating the tr leakage to the IF strip. When amplified and detected, this signal simulates a 95-knot Doppler input signal. Hence it provides a rough qualitative check of over-all system operation.

The outputs of the IF amplifier are signals having frequencies (30 mc$+\Delta f$) and (30 mc$-\Delta f$). These outputs are applied to the 1N69 crystal diode detector, whose output is a spectrum of frequencies, as shown in Fig. 12. The usable portion of the spectrum contains a narrow band of frequencies whose center is $2\cdot\Delta f$. Other frequencies present in the detector output are generated by noise, by the prf, by harmonics of the prf, and by all sum and difference combinations. A low-pass filter at the audio amplifier input attenuates all frequencies above 19.5 kc, passing the usable Doppler spectrum. The signal is amplified in two stages and applied to a cathode follower output. An agc circuit maintains the audio amplifier output at a maximum of 0.9 volt. In addition, the IF agc voltage is applied whenever strong Doppler signals are received. This prevents distortion of such signals by the audio amplifier, thereby avoiding the possibility of passing strong higher order harmonics to the frequency tracker. The audio amplifier response curve is flat within ± 0.3 db over any 20 per cent of its range.

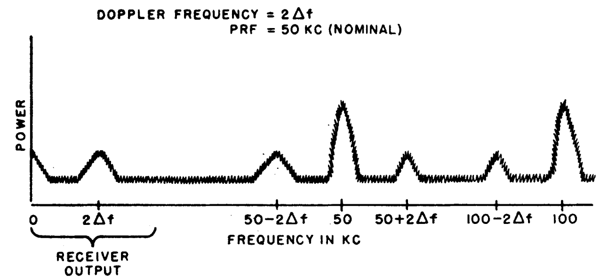

Fig. 12—Second detector output.

The useful output of the receiver is therefore a spectrum of frequencies whose center frequency is the desired Doppler frequency. (Actually there are two spectra, corresponding to the left-right antenna switching periods.) The bandwidth of this spectrum is normally about 10 per cent of the center frequency value. The amplitude of the spectrum varies from 0.9 v rms at low signal-to-noise values to 0.35 v rms at high signal-to-noise values. The Doppler spectrum is accompanied by broad-band circuit noise; in addition to being valueless in the determination of the Doppler frequency, this noise can attain a level which prevents the frequency tracker from functioning normally. In the latter case, the system is forced into a memory mode of operation. Fig. 9 shows an idealized Doppler spectrum.

Ground-Speed Computation

The "frequency tracker" computes ground speed from the receiver output. Physically, these frequency tracker elements are located in the AM-758A/APN-81, the AM-742/APN-81, and the CP-185/APN-81.

The basic function of the frequency tracker is to measure the Doppler frequency accurately and continuously, smoothing instantaneous frequency variations, and to provide a usable output which is an analog of ground speed. In addition, the frequency tracker, together with the antenna, measures drift angle. Fig. 13 is a block diagram of the frequency tracker main loop. The local oscillator (lo) frequency is variable from 26 kc to 43 kc, depending on the applied control voltage. The control voltage applied to the lo is a dc voltage on which is superimposed a 35-cps square wave. Hence the

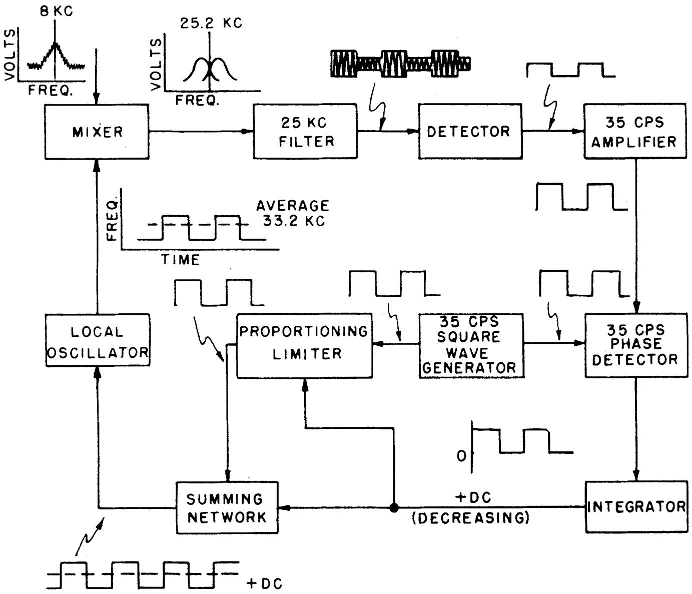

Fig. 13—Frequency tracker main loop.

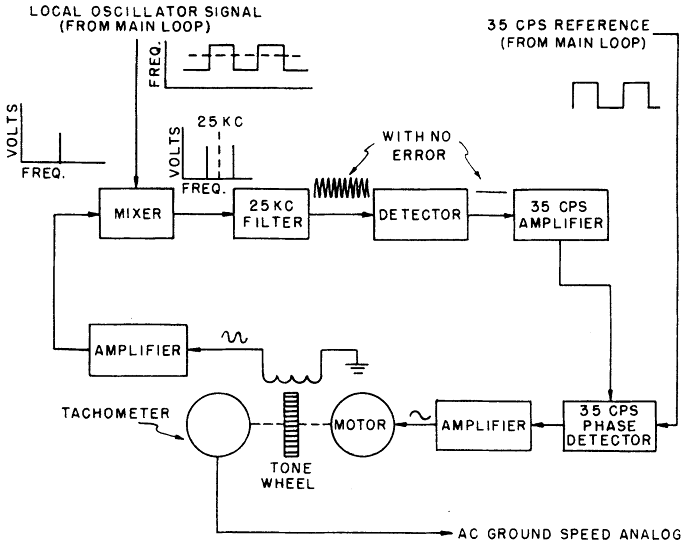

Fig. 14—Frequency tracker rate loop.

lo is frequency modulated at a 35-cps rate above and below an average frequency determined by the average dc level of the control voltage.

The function of the main loop is to keep the lo average frequency 25 kc above the average Doppler frequency. Since the lo average frequency is a direct function of the average dc control voltage applied to it, the latter voltage is then an analog of ground speed.

Assume that the antenna is on ground track, so that the center frequencies of the Doppler spectra obtained from the right and left returns are identical. Consider one of these spectra and assume that its center frequency is 8 kc, while the average lo frequency is 33.2 kc, or 25.2 kc above the Doppler frequency.

The lo is frequency modulated at a 35-cps rate above and below this 33.2-kc figure, producing two discrete frequencies of 33.6 kc and 32.8 kc. (This represents an lo switching range of 800 cycles, or 10 per cent of the Doppler frequency.)

The outputs of the lo are heterodyned in the mixer with the input Doppler spectrum. The output of the mixer thus consists of two spectra, alternating with one another at the 35-cps rate, with center frequencies (at 25.6 kc and 24.8 kc) equally spaced above and below 25.2 kc. These spectra are inputs to the narrowband 25-kc filter.

The characteristic curve of the 25-kc filter is symmetrical with respect to the 25-kc point. Hence the filter output for the higher frequency spectrum is less than the filter output for the lower frequency spectrum. The filter output thus has a 35-cps envelope. If the lo average frequency were exactly 25 kc above the Doppler frequency, the filter output envelope would be a straight line.

The detector removes the 25-kc carrier, and the resultant 35-cps square wave is amplified and applied to the 35-cps phase detector. Here it is phase detected against the 35-cps reference. The output of the 35-cps phase detector is a positive voltage whenever the lo average frequency is too high. The output of the 35-cps phase detector is an input to the integrator. With a positive error voltage applied at the input, the normally positive dc integrator output is decreased in amplitude. Since the integrator output is the dc control voltage applied to the lo, this causes the lo average frequency to decrease. This action continues until the lo average frequency is 25 kc above the Doppler frequency. An integrator is used at this point in the circuit in order to smooth the inherent fluctuations in the instantaneous Doppler input. Since the integrator output is the average dc control voltage applied to the lo to maintain it at 25 kc above the average Doppler frequency, it is also an analog of ground speed.

To obtain optimum discriminator sensitivity in the 25-kc filter, it is required that the lo frequency modulation be such that the 3-db points of the Doppler spectrum pass through the filter. Since the width of the Doppler spectrum is 10 per cent of the spectrum center frequency, the extent of lo modulation must be maintained at the same value. This is accomplished by the proportioning limiter, whose output is a 35-cps square wave whose amplitude is a function of the value of the integrator output.

The integrator output is mixed with the proportioning limiter output in a summing network to determine the lo control voltage.

Although the lo control voltage (dc) is an analog of ground speed, it is desirable to obtain an analog in terms of an ac voltage. This is accomplished by the frequency tracker rate loop (Fig. 14).

The tone wheel in the rate loop is a steel gear with its teeth mounted adjacent to the magnetic core of a pickup coil. As the gear rotates, the air gap in the magnetic field of the core varies at the rate of one cycle per tooth. Since this varies the circuit reluctance, the magnetic flux passes through alternate maxima and minima at this rate. This generates an alternating voltage in the coil; the frequency of the generated voltage is proportional to the rate of rotation of the tone wheel.

The function of the rate loop is to keep the tone wheel frequency at 25 kc below the lo average frequency. This keeps the tone wheel frequency equal to the average Doppler frequency.

The rate loop functions in a manner similar to the main loop, with the exception that discrete frequencies, rather than spectra, are involved. Assume that the average lo frequency is 33 kc. If the tone wheel frequency differs from the lo frequency by a value other than 25 kc, a 35-cps error envelope appears at the output of the 25-kc filter. This error envelope gives rise to a dc error signal at the 35-cps phase detector output. This changes the motor speed until the correct tone wheel frequency is obtained.

The Doppler frequency, plus the center frequency of the main loop 25-kc filter, minus the center frequency of the rate loop 25-kc filter, equals the tone wheel frequency. If the ground speed computation included only the main loop and the rate loop, the tone wheel frequency would differ from the Doppler frequency by an amount dependent on the accuracy with which the centers of the two 25-kc filters are matched. A third loop, the correction loop, is designed to match the rate loop filter, which is tunable, to the main loop filter. For about one second out of every 10, the tone wheel frequency is inserted into the main loop mixer in place of the Doppler input. At the same time, the output of the main loop 35-cps phase detector is fed into a correction integrator, which operates through a reactance tube to tune the rate loop filter. If the two filters are not matched, an error signal will appear at the input of the correction integrator. The latter, through the reactance tube, will tune the rate loop 25-kc filter to remove the error. A secondary advantage of the correction loop is that it permits relatively low precision components to be used in many places, since the errors contributed by such components are eliminated by action of the loop.

The usable output of the rate loop is generated by the tachometer shown in Fig. 14. The tachometer output is an ac voltage analog of ground speed, with a scale factor of one volt per 100 knots. This voltage is available as an output of the APN-81 (through a low impedance output amplifier), and is also used to drive a ground speed position servo.

The latter drives a synchro which transmits ground speed information to the ground-speed indicator, and positions an additional synchro for transmissions of data to navigational or other type computers.

Drift-Angle Computation

The left and right beams are switched alternately at 1 cps. If the antenna is on ground track, the Doppler frequency from the left beam is the same as the Doppler frequency from the right beam. If the antenna is off ground track (say to the left, as in Fig. 5), the Doppler return from the left beam is of lower frequency than the Doppler return from the right beam. The output of the main loop 35-cps phase detector then goes positive and negative alternately in synchronism with the 1-cps left-right switching.

Thus the output of the 35-cps phase detector contains an ac voltage at one cps. The phase and amplitude of this voltage are functions respectively of the direction of the antenna off ground track and of the magnitude of the error.

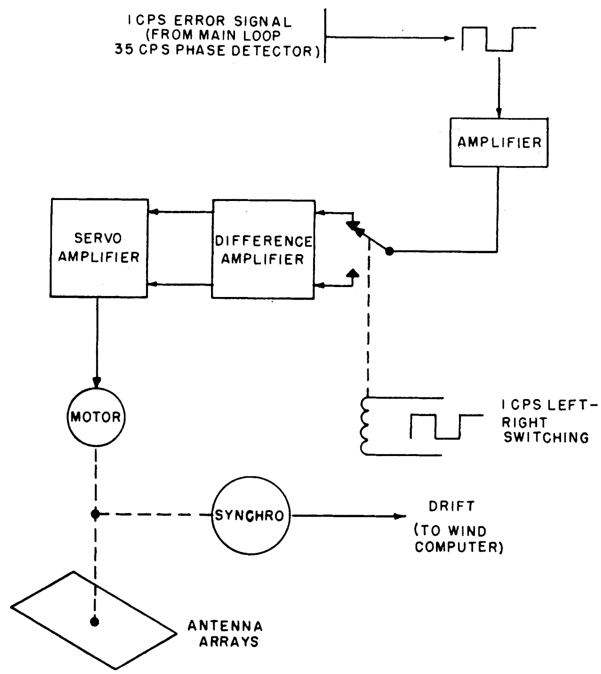

Fig. 15—Drift-angle computation.

As shown in Fig. 15, the output of the main loop 35-cps phase detector is amplified, and then phase detected against the 1-cps left-right switching reference at the input to the difference amplifier. The output of the difference amplifier is a dc voltage whose sense is a function of the direction of azimuth error. This error voltage is applied to a servoamplifier having a magnetic output, which drives the azimuth servomotor; the latter controls the antenna position. The system is phased so that the 1-cps error signal causes the motor to drive the antenna toward ground track until the error signal is zero. A tachometer, not shown in Fig. 15, provides rate feedback (applied to the servoamplifier).

A synchro control transformer, driven by the azimuth gearing, provides a measure of drift-angle value. This synchro is connected electrically to a transmitter synchro in the CP-185. The two synchros constitute the error source for a position servo. The drift-angle shaft in this position servo in the CP-185 drives a synchro which transmits drift angle information to the drift angle indicator and positions an additional synchro for transmissions of data to navigational or other type computers.

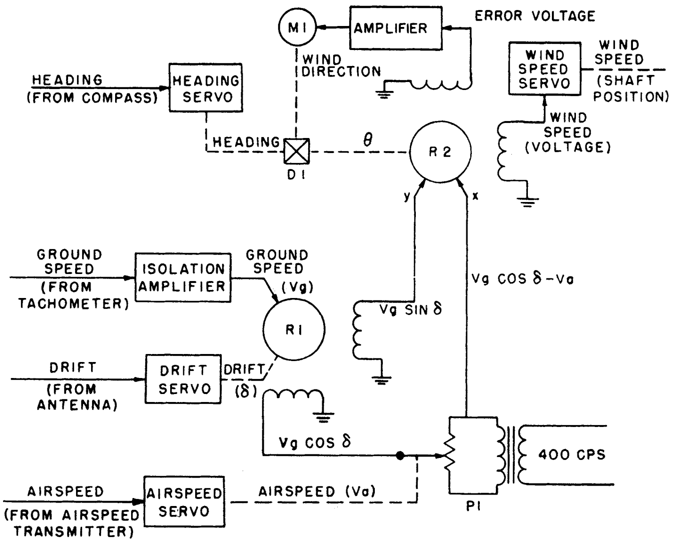

Fig. 16—Computation of wind (normal).

The Wind Computer

During the infrequent periods of *memory* operation, ground speed and drift angle are computed from remembered values of wind speed and wind direction, and from continuous-heading and air-speed inputs (Fig. 6). The wind-speed and wind-direction values are available during the *memory* modes, because they have been computed (when the system is in *normal*) from the ground-speed, drift-angle, heading, and air-speed values.

Relays control the memory computations. Certain of these relays may be actuated by the radar silence switch or by signal-to-noise circuitry in the AM-758A electronic control amplifier. The signal-to-noise circuitry consists of a differential detector which compares signal-plus-noise in the signal channel with noise alone. When the ratio of signal-plus-noise to noise becomes less than a predetermined power level, the system goes into *memory*.

The computations of wind speed and wind direction during the *normal* mode of operation are accomplished by components of an electromechanical analog computer. When the system is switched to the *memory* mode, the same components are utilized to reverse the computation and provide values of ground speed and drift angle.

Fig. 16 is a simplified diagram of the elements used in the computation of wind speed and wind direction. Heading and air-speed information are inputs from external compass and air-speed sources. Synchros receive these elements of data and by means of position servos turn shafts to values of heading and air speed.

The ground-speed ac voltage is applied to the rotor coil of synchro resolver R1. The coil is positioned by the drift-angle shaft. The voltages induced in the stator windings are, therefore, $Vg \sin \delta$ (side CB, or y, in Fig. 6) and $Vg \cos \delta$ (side AC in Fig. 6).

Potentiometer P1 is positioned by the input air-speed shaft. Connections to potentiometer P1 are such that the pot output is the difference $Vg \cos \delta - Va$ (in Fig. 6, $AC-AD$, or x).

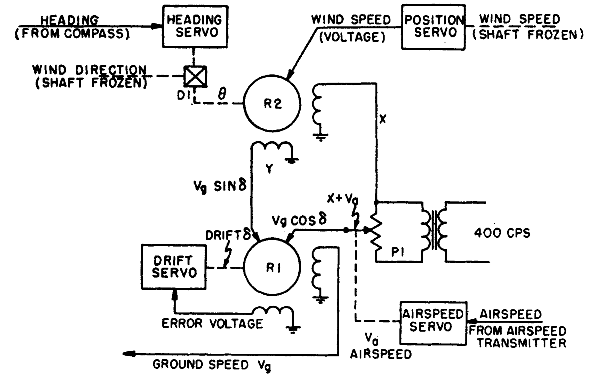

Fig. 17—Computation of ground speed and drift angle (memory).

The x and y voltages are applied (through isolation amplifiers, not shown) to the rotor coils of synchro resolver R2. One stator coil of R2 drives motor M1. Motor M1, through differential D1, turns the rotor shaft of R2. When the error voltage is at a null, the position of the rotor shaft represents the angle θ (of Fig. 6). From Fig. 6, it can be seen that the motor shaft position must then be the desired value of wind direction.

With the error voltage at a null, the voltage induced in the second stator coil of R2 is an analog of the required wind speed. Through a servo, this voltage positions a shaft to the wind-speed value.

In order to reduce the response of the wind servos to rapid wind fluctuations, tachometer feedback (not shown in Fig. 16) is used. The time constant of both the wind-speed and wind-direction servos is about 40 seconds. This effectively smooths the wind data.

Synchros on the wind-speed and wind-direction shafts can be used to transmit the computed wind information to external indicators or to meteorological recording equipment.

In the *memory* modes of operation, relays are actuated to "freeze" the wind-speed and wind-direction shafts at the last computed wind values. Heading and air speed are used with the wind data to compute ground-speed and drift-angle values, utilizing the same resolver components as in the *normal* mode. In addition, search circuits sweep the frequency tracker local oscillator through its frequency range in search of a usable signal. When a signal of sufficiently high signal-to-noise ratio is found, the system reverts to the *normal* mode.

Fig. 17 shows the computation of ground speed and drift angle during the memory mode. With the wind-speed shaft frozen, a voltage analog of wind speed is obtained from a potentiometer in the wind speed position servo. This voltage is applied (through an isolation amplifier, not shown) to one rotor coil of synchro resolver R2. The shaft of R2 is turned through the angle θ (of Fig. 6). The θ value is determined by the sum of the heading input and the frozen wind direction value.

The voltages induced in the stator coils of R2 are x and y (DC and CB of Fig. 6). The x voltage is added to the air-speed voltage at potentiometer P1. The sum is $(Va+x)$, $[(AD+DC)$, or $Vg \cos \delta$, in Fig. 6$]$. The $(Va+x)$ and y voltages are applied (through isolation amplifiers, not shown) to the rotor coils of synchro resolver R1.

The output of one stator coil of R1 is used as an error voltage to drive the rotor shaft of the resolver. When the error voltage is at a null, the shaft position is an analog of the drift angle. This shaft position, through synchros, then controls the antenna in azimuth. The voltage induced in the second stator coil is the required analog of ground speed. This voltage is utilized during the *memory* modes to control the tachometer and tone wheel in the frequency tracker rate loop.

Some Applications of the APN-81

Because of the high accuracy with which the APN-81 computes ground speed and drift angle, it can be utilized effectively to supply these elements of data to a variety of navigational and other type computers.[2]

One such application is the AN/APN-82 system, which consists of the APN-81 interconnected with the AN/ASN-6 navigational computer (built by Ford Instrument Company). The ASN-6 is an electromechanical dead-reckoning navigational computer. Automatic inputs to the ASN-6 in this interconnection are ground speed and drift angle from the APN-81 and compass heading from a standard compass system. Manual inputs are magnetic variation and present position fixes in latitude and longitude. Outputs are continuous values of present latitude and present longitude. Accuracy obtainable from the APN-82 is on the order of 1 per cent to 2 per cent of total distance traveled.

The APN-99 consists of the APN-81 interconnected with the AN/ASN-7 navigational computer (built by the Ford Instrument Company). The ASN-7 incorporates all of the features of the ASN-6, plus a rhumb-line course angle and distance-to-destination computer.

Another navigational application is the APN-66 system, which consists of the APN-81 interconnected to the AN/APA-95 navigational computer (built by General Precision Laboratory Incorporated). The APA-95 is a highly accurate dead-reckoning present-position computer, together with a great circle course angle and distance-to-destination computer. Automatic inputs to the APA-95 are ground speed and drift angle from the APN-81, and flux valve and directional gyro information. The latter two inputs are required for the true heading computer in the APA-95 (this computer utilizes a three-dimensional cam to provide automatic magnetic variation data, and also includes continuous longitude rate information to correct the measured heading for aircraft transport error). The only manual inputs required by the APA-95 are present latitude and longitude fixes and the insertion of destination latitude and longitude. Outputs are continuous values of present latitude and longitude, great circle course angle, and distance to destination. In addition, a steering error signal is provided to the aircraft's autopilot and can be furnished to a PDI. The APA-95 operates completely automatically over all parts of the earth's surface, whereas the ASN-6 and ASN-7 computers require special operational techniques for polar use. Accuracy of the APN-66 is within 1 per cent of total distance traveled.

In addition to these interconnections, the APN-81 system has been utilized to compute "spot" winds, either with the standard 40-second wind servo time constant or with a modified wind computer wherein a 15-second time constant is used. In this application, special wind-speed and wind-direction indicators or recorders are used.