DOPPLER NAVIGATION RADAR

GENERAL

The problem of navigation resolves itself into several fundamental questions. Where am I, where am I going, and how fast am I going there? Under ideal conditions, the airspeed indicator and compass would furnish precise answers to the last two questions. However, under normal flying conditions, wind adds a factor which causes the compass and airspeed indication to vary greatly from true ground track and ground speed. The APN-147 Doppler radar system gives the answer. Its advantages are that it operates without the need of any auxiliary ground station; it is capable of operating day or night; it is capable of operating in any weather condition; and it is capable of operating at any latitude.

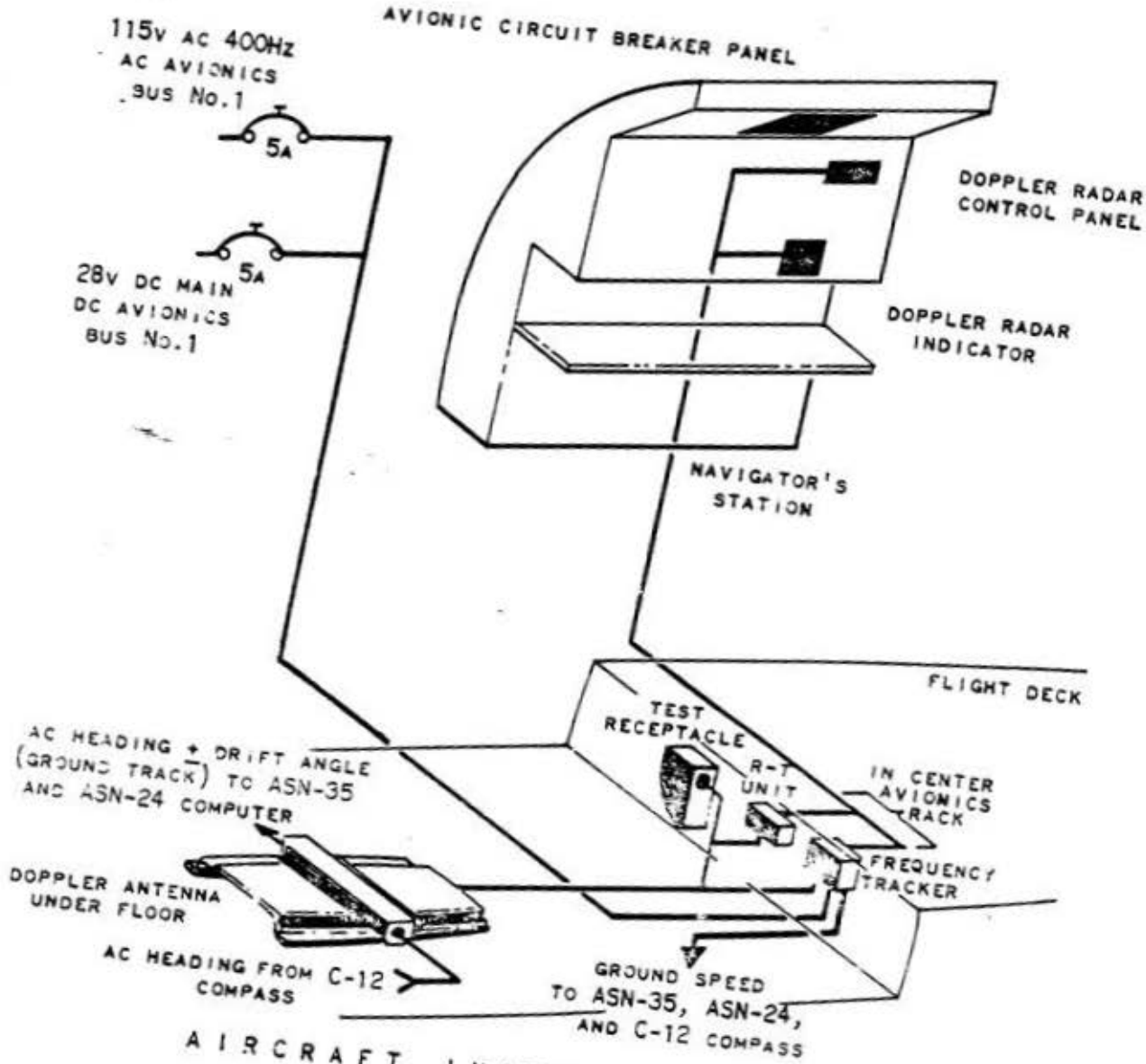
The APN-147 measures and displays aircraft ground speed and drift angle. Ground speed is the actual rate of travel over the earth's surface. Drift angle is the angular difference between aircraft heading and the path that it follows over the earth. Ground speed is displayed in nautical miles per hour (knots) on the navigator's instrument panel. It is also supplied to the ASN-35 Doppler computer, the ASN-24 computer and the C-12 compass. Drift angle is displayed on the navigator's panel as degrees left or right of ground track. Drift information is also supplied to the ASN-35 and ASN-24 computers.

AIRCRAFT INSTALLATION

The Doppler system consists of five components. They are as follows:

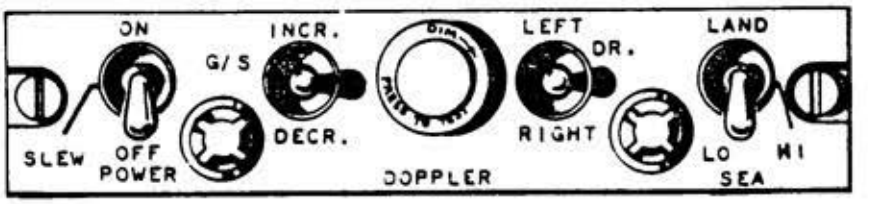
- Transceiver — RT-625 ( )
- Antenna — AS-1168
- Frequency tracker — CV-1181
- Indicator — ID-938
- Control panel — C-3818 ( )

A test receptacle is also provided on the side of the navigation J box. The location, power sources, and cabling is shown on the "Aircraft Installation" illustration.



AIRCRAFT INSTALLATION

SYSTEM OPERATION



CONTROL PANEL

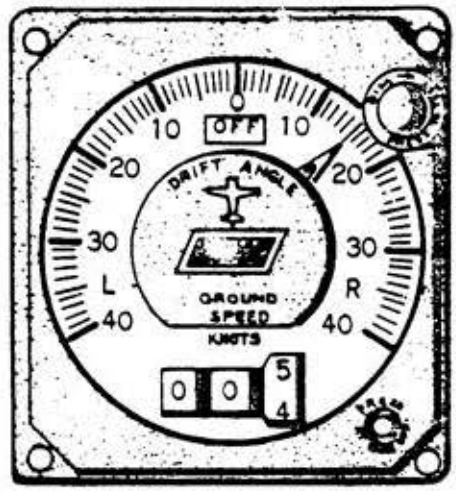
The control panel and indicator at the navigator's station contains the necessary controls for system operation. The POWER switch is used to energize the system for manual slewing ("SLEW" position) and automatic operation ("ON" position). In the "SLEW" position ground speed and drift angle momentary slew switches are enabled. The slew switches allow the operator to manually insert estimated aircraft ground speed and drift angle values into the system. If the inserted values are near actual values the radar will acquire "lock-on" in flight after the POWER switch is placed to "ON". After "lock-on" the radar will automatically track any change in ground speed or drift angle and will continuously maintain drift angle and ground speed indications. The slew switches are disabled when the POWER switch is in the "ON" position.

The LAND-SEA switch provides proper corrections of ground speed readings for the type of surface over which the aircraft is flying. The "LAND" position of the LAND-SEA switch is used when the set is operated over land. When flying over water sea-state error results in the reduction of the Doppler shift as the radar waves are reflected from the water. This reduction of Doppler shift would result in a decreased ground speed read-out if it was not compensated. 1.25 percent correction is necessary due to this error. The "SEA-LO" switch position is used when flying low over water and when returns are sufficiently strong to maintain constant "lock-on", however the ground speed reading is corrected 1.25 percent and remains accurate. At higher altitudes where return signal strength is lower, the "SEA-HI" position is used. Depending on the sea condition (smooth) the amplitude of the received signals is also reduced. In the "SEA-HI" position two modes of operation are possible: "SEA-HI" operation which is similar to "SEA-LO" operation, and Smooth Sea operation where antenna beam angle is increased in order to maintain "lock-on". Smooth Sea is less accurate than "SEA-HI". In actual operation the set automatically cycles between the two modes approximately every 60 seconds unless "lock-on" is achieved in the "SEA-LO" operation. In this event "SEA-LO" operation is maintained until loss of the return signal occurs.

NOTE: The automatic cycling described occurs only when the LAND-SEA switch is in the "SEA-HI" position.

Insufficient signal or system malfunction are indicated by memory lights on the control panel, and by an OFF flag and memory light on the indicator. The indicator displays drift angles of 40 degrees left or right and ground speed up to 999 knots. Maximum drift is limited to 38 degrees left or right in the antenna.

A pre-takeoff pushbutton on the indicator, when momentarily pressed, provides preset selection of ground speed and drift angle. The ground speed indicator will slew to 165 knots and the drift indicator will slew to 0 degrees. The pre-takeoff pushbutton is disabled by a touchdown relay when pressure is relieved from the main landing gear at lift-off.



GROUND SPEED INDICATOR

SPECIFICATIONS

DOPPLER RADAR APN-147

CHARACTERISTIC	SPECIFICATION
Operating frequency	8.8 GHz
Nominal Doppler frequency shift	20.66 Hz/knot (LAND mode) 20.48 Hz/knot (SEA mode) 6.67 Hz/knot (smooth Sea mode)
Emission type	FM-CW
Modulation	Sinusoidal 0.67 or 1.08 MHz
Power output	500 Milliwatts nominal 370 Milliwatts nominal
Operating altitude	100 feet to 50,000 feet
Drift angle	Up to maximum 40 degrees L or R $\pm$1/4 degrees

SPECIFICATIONS (continued)

DOPPLER RADAR APN-147

CHARACTERISTIC	SPECIFICATION
Ground speed	70 KT to 1000 Kt $\pm$ 5 percent
Antenna attitude limits	Pitch $\pm$ 20 degrees, stabilized $\pm$ 1 degree Roll $\pm$ 30 degrees
Antenna drive rates	Pitch 1 degree per second Drift 3 degrees per second

BLOCK DIAGRAM THEORY OF OPERATION

The Doppler radar measures groundspeed and drift angle using the "Doppler Effect". The "Doppler Effect" is the frequency shift induced into a signal when the transmitter or receiver, or both, are in motion in relation to each other. The amount of Doppler shift is directly proportional to the aircraft velocity (groundspeed) and can be expressed by the mathematical formula:

$$\text{Doppler shift} = F\frac{V}{C}$$

Where F = frequency transmitted

V = velocity of aircraft (groundspeed)

C = speed of light (propagation velocity of radar wave)

The Doppler shift is upward ("Up-Doppler") on a beam transmitted forward of a moving aircraft and downward ("Down-Doppler") on a beam transmitted aft. Two other factors must be considered when the Doppler shift is measured by a radar set in an aircraft. First, since both the transmitter and receiver are located in the aircraft, two Doppler shifts are created. One when the wave is transmitted and the second as it is reflected back to the aircraft. A factor of two must now be added to the Doppler formula.

$$\text{Doppler shift} = 2\ F\ \frac{V}{C}$$

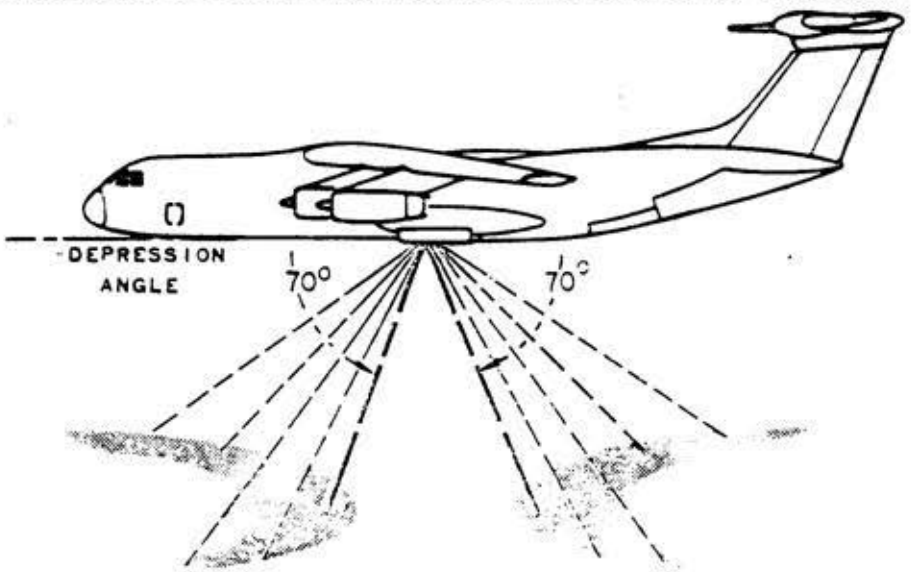
The second factor that must be considered is the angle of antenna radiation. Maximum Doppler shift would be received if the antenna beam was transmitted dead ahead. If the beam was directed straight down at the earth, the Doppler shift would be minimum. Since in the aircraft the beam is directed to the ground at an angle between dead ahead (0 degrees) and straight down (90 degrees), we introduce a factor to compensate for this. The factor used is the cosine of the radiating

angle. The complete Doppler formula then becomes:

$$\text{Doppler shift} = 2\ F\frac{V \cos \text{radiating angle}}{C}$$

The Doppler shifts incurred, above and below the transmitted frequency, are detected and converted into an audio signal within the Doppler system at the nominal frequency of 10.33 Hz per knot of groundspeed. The audio signal is used for groundspeed and drift angle computations.

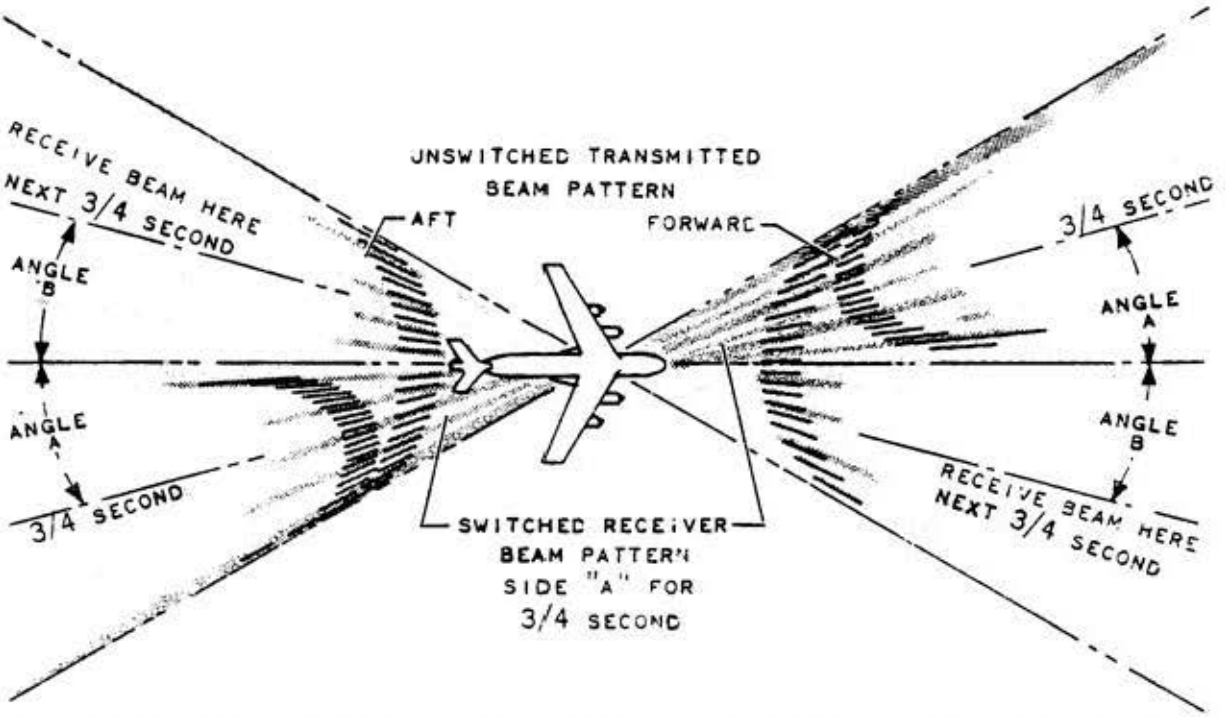
The Doppler system transmits one fan-shaped beam forward and one aft. The transmitted beams are angled below the aircraft, fore and aft at a 70 degree depression angle. This creates an RF energy pattern on the ground much like the illumination pattern of a flashlight beamed at an angle onto a tabletop.



TRANSMITTER BEAM PATTERN

Two receiver beams are utilized simultaneously, one looking forward, the other looking aft. This ability of a radar set to look in two directions at once is called "Janus" operation. The fore and aft beams are offset from the centerline of the aircraft and are switched from side to side at a 3/4 second rate. During the first 3/4 second period the received beams cover the right forward and left aft segments of the transmitted patterns. For the next 3/4 second the beams cover the left forward and right aft segments.

The tracker circuits measure groundspeed by determining (frequency tracking) the Doppler shift. The difference between the Up-Doppler and Down-Doppler frequencies is detected to produce a Janus Doppler audio signal which is the sum of the two Doppler shifts and is representative of groundspeed. The Janus Doppler signal is used to drive a servo. Rotation of the servo shaft, which is analogous to groundspeed, controls a servo loop which positions the digital groundspeed readout on the indicator.



In "LAND" mode each knot of ground speed creates a Doppler shift of 20.66 Hz Janus audio. Janus audio is 20.40 Hz per knot in either "LO SEA" or "HI SEA" modes. "Smooth Sea" is an automatic function of the manually selected "HI SEA" mode. Smooth Sea operation occurs when the received signal strength is inadequate to provide normal "SEA" operation. In Smooth Sea operation the forward beams tilt down an additional 7 degrees and the rear receiver beams are disabled. The additional depression angle and loss of the rear beams results in a lower Doppler shift (6.67 Hz/knot non-Janus). For one minute out of every two, the system returns to normal Janus operation. If, during this one minute period adequate signal is being received, the system remains in Janus operation and does not return to Smooth Sea until the received signal again decreases below a usable level. If sufficient signal is received only in Smooth Sea mode it is normal for the memory light to illuminate approximately one minute out of every two.

Drift angle is measured by comparing the average Doppler shift incurred in one 3/4 second period to the shift incurred in the alternate 3/4 second period. Assuming a drift condition exists (aircraft heading and ground track are not the same) the Doppler shift will be greater in one receiver beam position than in the other. As long as a 3/4 second change in Doppler shift exists, a servo within the tracker will position the antenna, right or left from the aircraft centerline, until a steady Doppler condition is reached. The antenna centerline will then be along the ground track. Drift angle is the angular difference between aircraft centerline and antenna centerline. A synchro loop, controlled by antenna movement, positions the drift angle needle on the indicator.

A built-in sampling (lock-check) circuit determines if the displayed information is accurate by introducing errors into the system and checks for the correct response. If the response is incorrect or the received signal is inadequate to sustain Janus or Smooth Sea operation the system goes into memory. While in

mory the indicator is automatically locked to the last valid ground speed and ift angle readings. The warning flag appears and the memory lights are illuminated. While the system is in memory, a continuous check of the received signal is made to determine whether its strength is adequate to restore normal Janus or Smooth Sea operation.

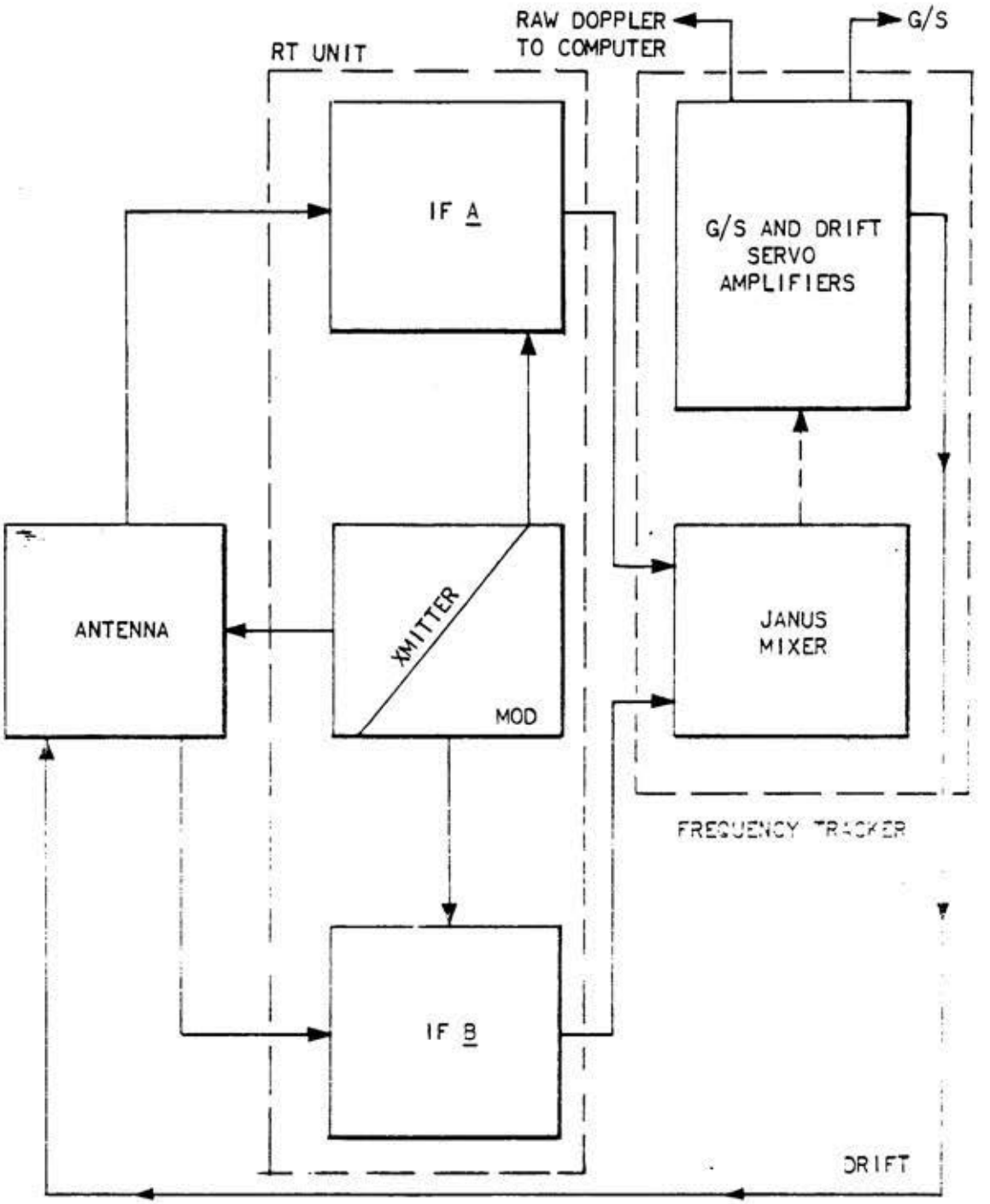
The Doppler transmitter produces a Frequency Modulated (FM) Continuous Wave (CW) carrier. The modulation signal is generated in the modulator and applied to the transmitter klystron. The klystron output is applied to the transmitting antenna.

The returned signals are amplified in two IF strips and sent to the Janus mixer. The Janus mixer adds the Up-Doppler and Down-Doppler from the IF strips. The Janus Doppler then supplies the frequency comparator. The frequency comparator locks a linear voltage controlled audio oscillator to the Doppler audio frequency. The shaft angle of the oscillator-driving servo is transmitted to the indicator as an analog of groundspeed.

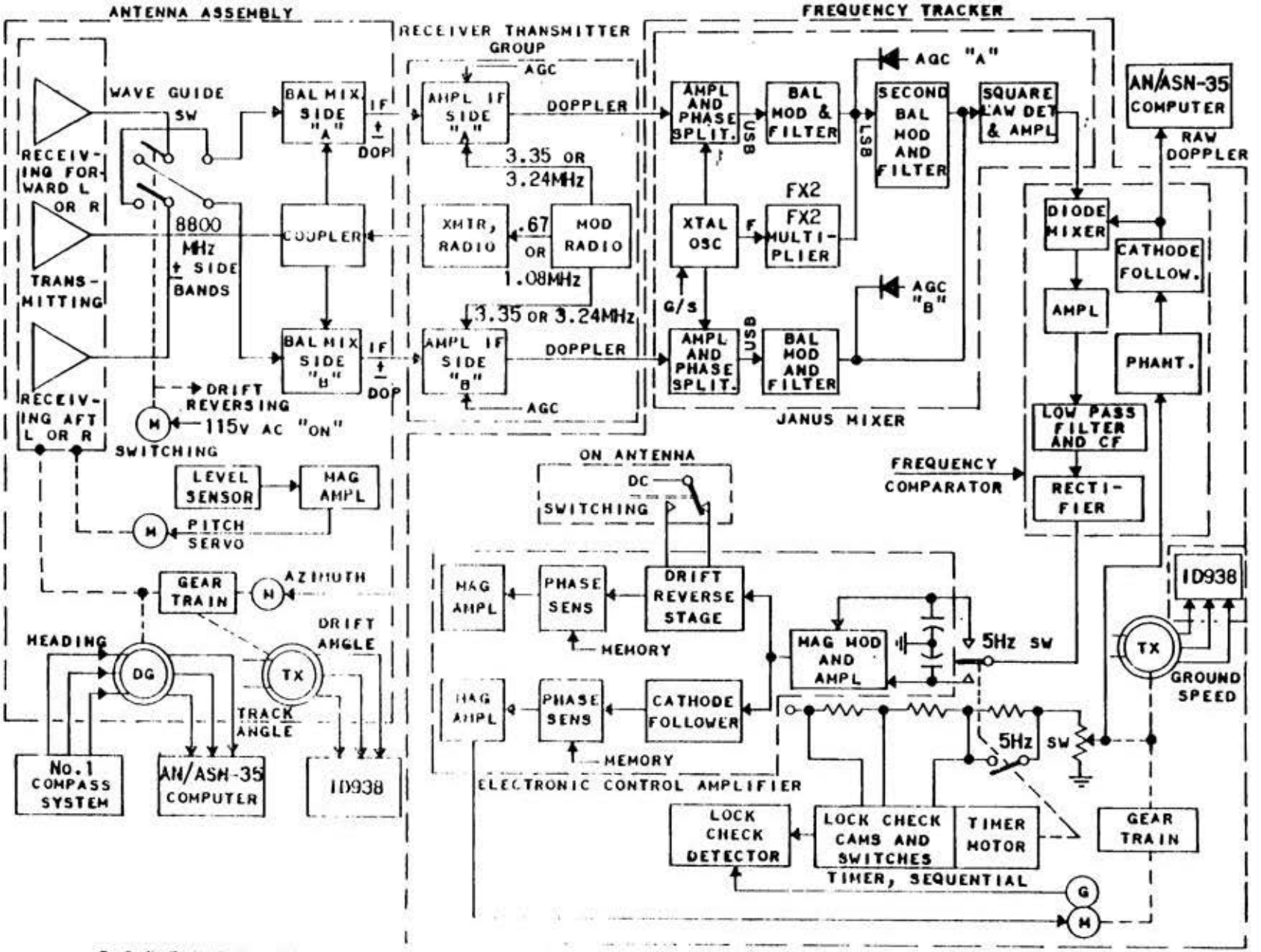
The modulator generates signals of 0.67 or 1.08 megahertz (MHz). The frequencies are switched alternately at a 15 Hz rate. Multiplying stages select harmonics nearest 3.3 MHz from each signal. These multiplied frequencies are used by the receiver. The 15 Hz time-shared 0.67 or 1.08 MHz signal is superimposed upon the D-C repeller voltage supply of the transmitting klystron. The klystron output is an 8,800 MHz, frequency modulated carrier with the modulating signal plus harmonics of the modulating signal appearing in the sidebands of the carrier. The klystron output is fed through a coupler to the transmitting array. This array consists of a slotted waveguide with a horn reflector. The slots are cut to direct a fan-shaped beam forward and aft at equal angles to the aircraft centerline. The coupler directs a small sample of the transmitted energy to the receiver mixers.

The receiving array consists of two slotted waveguide sections joined back to back. One is slotted to receive forward, the other aft. The received beamwidth is approximately one-half the width of the transmitted beams. The reflectors are shaped to direct the received beams to the left or right half of the transmitted beams. When the forward beam is being reflected left, the aft beam is reflected right. Three-quarters of a second later the waveguide assembly is rotated 180 degrees. Now the forward beam is reflected right, the aft beam left.

A waveguide switch connects the output from the arrays to the balanced mixers. The balanced mixers beat the sample of the transmitted energy from the coupler, with the incoming reflected energy. The result is a broad spectrum of frequencies consisting of the harmonic sidebands and the Doppler frequencies. Included is the IF plus or minus the Doppler. This signal is the third or fifth harmonic of the 0.67 or 1.08 MHz modulating frequencies. This signal is fed to the IF amplifiers. The IF is stagger-tuned for broad-band operation. The IF plus or minus Doppler frequency is mixed with the signal from the multiplier in the modulator.



DOPPLER RADAR SYSTEM BLOCK DIAGRAM



DOPPLER RADAR SYSTEM FUNCTIONAL BLOCK DIAGRAM

Rectifying and filtering yields the Doppler frequencies. The output of the right IF amplifier will be Up-Doppler, while the output of the left IF amplifier is Down-Doppler. Three-quarters of a second later this condition is reversed as antenna switching occurs.

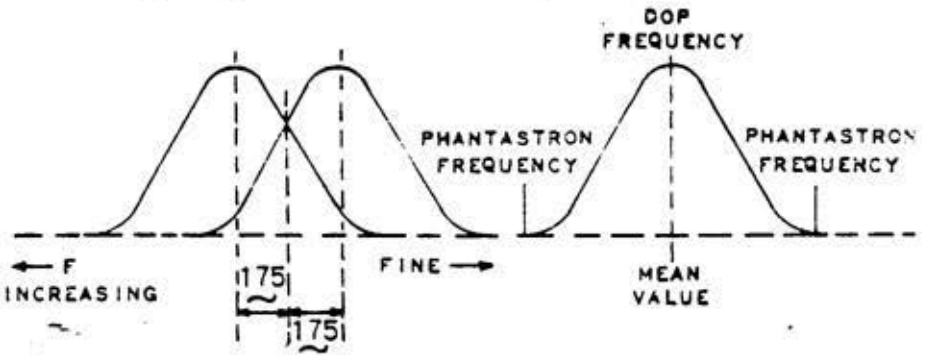
The outputs of the IF amplifiers are connected to the frequency tracker unit, where they are applied to the Janus mixer. The purpose of the Janus mixer is to add the Up-and-Down Dopplers. This is accomplished by producing single sideband signals using approximately 100 kilohertz as the carrier frequency. By selecting the upper sideband of one balanced modulator and the lower sideband of the other, the sum of the Doppler shifts can be obtained through a "square law detector".

In the amplifier and phase splitter circuits the Up Doppler and Down Doppler is added to a carrier from the crystal oscillator. For explanation purposes we will assume that the Crystal Oscillator frequency is 100 KHz. In the balanced modulator and filter circuits the sum and difference frequencies are obtained and the carriers are suppressed. Upper Sideband (USB) filters eliminate the lower sideband. As an example if Up Doppler and Down Doppler were both 5 KHz then the output of each of the USB filters would be 105 KHz. The crystal oscillator frequency is doubled (200 KHz) and mixed with the output from one of the USB filters. In our example 105 KHz out of the USB filters would result in sum and difference frequencies of 305 and 95 KHz being applied to the Lower Sideband (LSB) filter. The LSB filter then passes 95 KHz to the square law detector where it is mixed with the 105 KHz from the other USB filter to produce a Janus Doppler signal of 10 KHz (difference frequency). In actual usage the input Doppler frequency will vary from 1 to 10 KHz as groundspeed changes. This results in a change of 2 to 20 KHz of Janus Doppler.

The bandwidth of the USB filters is approximately 100.5 to 106 KHz. If the Crystal oscillator frequency was maintained at 100 KHz then at higher Doppler frequencies the sum of the crystal oscillator and Doppler frequencies would be above the USB filter range. To compensate for this the actual frequency of the crystal oscillator is changed from 99.8 to 96.9 to 95.1 as groundspeed is increased.

The Janus Doppler is then fed through an amplifier to the frequency comparator. The frequency comparator generates a shaft position analog of groundspeed by slaving a linear-voltage-controlled audio oscillator (phantastron) to the Doppler frequency. This shaft position is used by the navigator's groundspeed indicator. Frequency comparison is accomplished by mixing the output of a phantastron with the incoming Doppler signal through a diode mixer. The output of the mixer is amplified and fed to low-pass filter. If the phantastron frequency is considerably larger or smaller than the Janus Doppler frequency, the filter rejects the beat note produced in the mixer. As the phantastron approaches the Doppler frequency, the beat note is reduced in frequency until it is within the bandpass of the filter. The filter output is rectified, producing a D-C voltage when the phantastron is near the Doppler frequency.

The phantastron may be either above or below the Doppler frequency and produce a beat note within the bandpass of the filter. A five-cycle switch alternately shorts out and opens around a resistor in series with the phantastron potentiometer. This superimposes a five-Hz square wave upon the D-C phantastron control voltage. This change in control voltage causes an up and down shift in the phantastron output frequency at a five cycle rate. If the mean value of the phantastron frequency is centered in the spectrum of Doppler frequencies the phantastron shifts equal amounts above and below the Doppler frequency. The beat note is of the same frequency and amplitude during both frequency periods. A constant D-C voltage is produced. The five cycle switch causes the DC to charge



PHANTASTRON FREQUENCY VS
FREQUENCY SPECTRUM

the two capacitors at the input to the magnetic modulator. Since the D-C voltage is constant, both capacitors have equal charges and no current flows in the magnetic modulator input.

If the phantastron frequency is not centered about the Doppler frequency, the beat note is higher in frequency during one switching period than the other. The output of the filter is greater during one cycle; therefore, the rectified output is also greater. The action of the five cycle switch causes one capacitor to be charged to the higher voltage and the other to the lower voltage. Since the switch controlling the charging of the capacitors is operated at the same rate as the switch causing the phantastron frequency shift, the capacitor receives the higher charge if the mean phantastron frequency is above the Doppler frequency. This reversing D-C current flows in the input of the magnetic modulator when an unbalance in capacitor charge exists. The direction of the current flow depends upon the relative location of the mean phantastron frequency with respect to the Doppler frequency.

The magnetic modulator converts this DC into an A-C output with phase controlled by the polarity of the D-C input. This AC is applied through a cathode follower to a phase sensitive detector whose output controls a magnetic amplifier. The output of the magnetic amplifier is an A-C signal of sufficient amplitude to drive the groundspeed motor. The direction of motor rotation is controlled by the phase of the driving voltage. The motor drives the phantastron control potentiometer

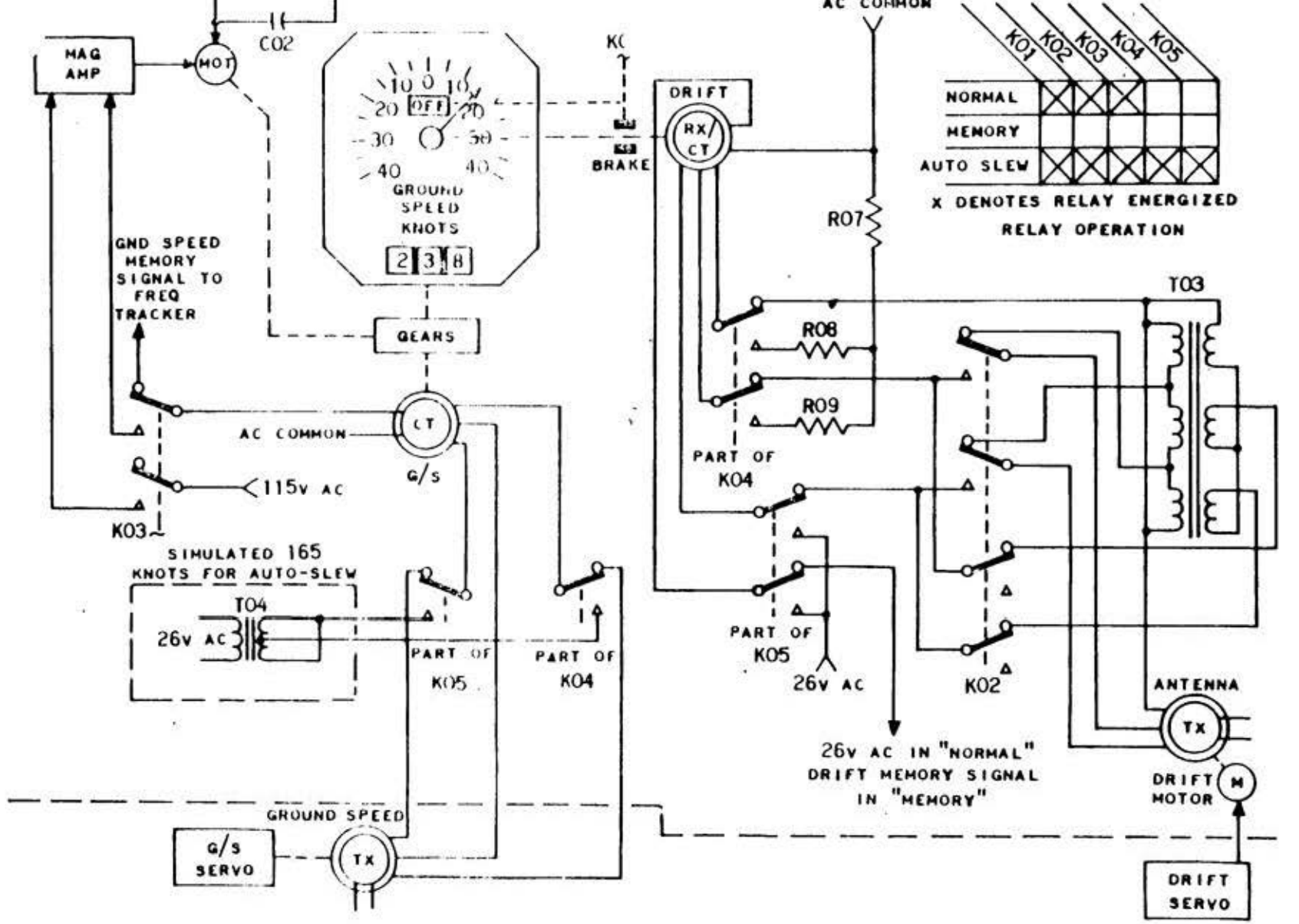
either in an increasing or decreasing frequency direction until the mean frequency is centered about the Doppler frequency. Switches on the groundspeed shaft change the carrier frequency in the Janus mixer crystal oscillator to the different valves needed to keep the mixed signal within the USB filter ranges. A synchro mounted on the shaft transmits an analog of groundspeed to the navigator's indicator.

The foregoing discussion presumed that the Doppler frequency remained constant. If there is an antenna drift error, the Doppler frequency is higher for one period of antenna switching than the other. The frequency tracker therefore tends to track upward (in frequency) for approximately three-quarters of a second, then downward for three-quarters of a second. This is due to the effect of the beam angle on the Doppler. Since the voltage causing the frequency to track upward and downward is related to the antenna switching rate, the same voltage can be used to position the antenna to null out the difference in frequency. The two halves of a drift reversing stage are alternately enabled by a switch on the antenna. The drift reversing stage will either pass the signal as is or reverse the signal phase, depending on the instantaneous antenna switching state. This process keeps the antenna driving in the proper direction until the frequency differences due to antenna switching are nulled out.

Drift angle is determined from the antenna position and is transmitted to the navigator's indicator by a synchro. The synchro rotor is geared to the antenna; its stator is clamped to the antenna saddle.

If the phantastron is initially positioned too far from the Doppler frequency, the filter output would be zero. The capacitors at the magnetic modulator input would not be charged and the system would appear to be locked on. To prevent this, a lock-check system is used. The lock-check system adds or subtracts resistances every 3.5 seconds in series with the phantastron potentiometer. This causes the groundspeed servo to be driven briefly upward then downward at a 3.5 second rate. A tachometer generator is connected to the groundspeed shaft. The tachometer output is connected to a detector which is gated by the lock-check switches. If the motor turns according to the error introduced by the lock-check switches, the detector output will hold the lock-check relay energized. If the motor does not drive, or turns in the wrong direction, the relay will deenergize and place the system in memory operation.

The navigator's indicator normally receives groundspeed and drift in the form of synchro signals. A control transformer and servo displays groundspeed on a drum-type counter. Drift is displayed by a synchro repeater and pointer. In memory operation, the drift pointer and groundspeed drums are locked. The synchros in the indicator are then used as a reference to hold the groundspeed and drift servos in the frequency tracker in their last position. The position is held until the radar is able to lock on the returned signal. The memory outputs of the indicator are fed into the phase sensor in the electronic control amplifier.



GROUND SPEED DRIFT ANGLE INDICATOR CIRCUITS