- Multimode antenna for amplitude comparison direction finders (eg Adcock antenna)
- Interferometer and phase mode direction finder

For high DF accuracy (eg 1°) and large bandwidth (eg 1 MHz to 30 MHz or 20 MHz to 1000 MHz) five to nine aperture probes are usually required. Since monopulse solutions would then be very complex, one fixed and two sequentially switched receive sections are frequently used.

The DF converter converts the carrier-frequency antenna signals to a fixed IF. Since this conversion must be made with equal phase and amplitude in all receive sections, the use of a common synthesizer is indispensable. Moreover, with most multireceiver direction finders the receive sections are calibrated with the aid of a test generator prior to the DF operation proper in order to ensure equal amplitude and phase.

The evaluation unit determines the bearing from the amplitudes and/or phases of the IF signals.

3 Classical DF methods

3.1 Using directional antennas

Evaluating the receive voltage of a mechanically rotated directional antenna with reference to the direction is the simplest way of direction finding. With this method the bearing is derived from the characteristic of the receive voltage as a function of the antenna rotation angle: when a wave arrives, the receive voltage yields the directional pattern of the antenna. The pattern position relative to the antenna rotation angle is the measured bearing.

This type of direction finder is by nature a phase direction finder since the directivity of its receiving antenna is achieved by superimposing partial waves whose phase differences depend on the angle of incidence. In the simplest case, the rotation of the antenna and the bearing determination are carried out by the operator. The antenna is rotated until the receiver output voltage assumes an extreme value. The antenna direction thus found is read from a scale and the bearing determined therefrom. If the directional antenna (with maximum or minimum pattern) is permanently rotated with the aid of a motor and the receive voltage displayed graphically as a function of the angle of rotation, a socalled spinning-wheel direction finder is obtained (Fig. 6). With suitable automatic evaluation, eg using a maximum detector, a fully automatic direction finder is obtained.

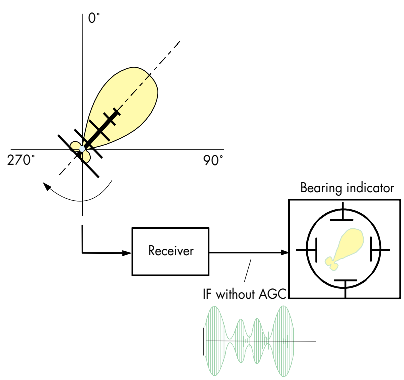

Fig. 6: Direction finding using directional antenna

The following benefits are common to all variations of this DF method:

- High sensitivity due to the directivity of the antenna
- Simple and inexpensive realization (only one receiver required, single-channel principle)
- Resolution of multi-wavefronts possible (prerequisite: different angles of incidence and high-directivity antenna system)
- Same antenna can be used for direction finding and monitoring

The drawbacks of this method result from the field of view that is inevitably restricted due to the directivity and from the rotating speed of the antenna that is limited by the mechanical antenna rotor:

- Probability of intercept is reciprocal to the directivity
- Method fails in case of short-duration signals, ie signal dwell times that are short compared to the period duration of the antenna movement

Despite these drawbacks DF methods using mechanically rotated directional antennas are still in use today since the advantages of other methods can be achieved partly only with a considerably higher outlay. Especially in the microwave range the mechanical DF method often is the only justifiable compromise between gain, low noise and outlay.

If in addition to the directional pattern with maximum in the direction of wave incidence a directional pattern with minimum is used, a monopulse direction finder is obtained which even with a slowly rotating or fixed antenna furnishes bearing as long as the waves arrive within the main receiving direction of the antenna. Fig. 7 shows the implementation with log-periodic dipole antennas connected with the aid of a 0°/180° hybrid. The directional patterns shown in the picture on the right are thus obtained.

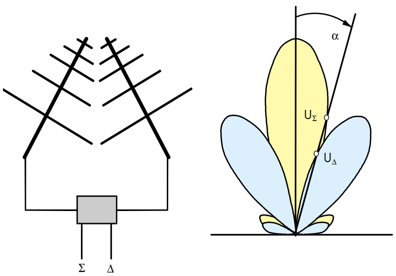

Fig. 7: Direction finding using sum-difference method: typical realization on the right, directional characteristics for sum(Σ) and difference (Δ) outputs on the left

The quotient between the difference and the sum signal yields a dimensionless time-independent function, ie the DF function

$$PF(\alpha) = \frac{U_\Delta(\alpha)}{U_\Sigma(\alpha)} \quad .$$

After forming the quotient of the two test voltages, the DF function immediately produces the bearing α.

3.2 Watson-Watt principle

If the boosted and filtered signals of a receiving antenna with outputs for the sine- and cosine-shaped directional characteristics are applied to the x and y deflection of a cathode ray tube, a line Lissajous figure is obtained in the ideal case, whose inclination corresponds to the wave angle but has a 180° ambiguity. The indicated angle is obtained from the ratio of the two signals

$$\hat{\alpha} = \arctan \frac{U_x}{U_y}$$

An unambiguous bearing indication is obtained (Fig. 7) if a blanking signal, derived from an omnidirectional receiving antenna with unambiguous phase relationship is added to this DF principle implemented the first time in 1926 by Watson-Watt.

If the two voltages U_x and U_y exhibit a phase shift δ due to ambient interference (eg reflections), the displayed figure is an ellipse. The position of the main axis yields the bearing which is calculated from the voltages of the equation [9], [10].

$$\hat{\alpha} = \frac{1}{2} \arctan \frac{2|U_x||U_y|\cos\delta}{|U_y|^2 - |U_x|^2}$$

The main benefit of this method is the undelayed bearing indication and the monopulse capability over the full azimuth range.

Suitable antennas with sine- or cosine-shaped directions patterns are in particular

- loop antennas (or ferrite antennas) and
- Adcock antennas (monopole or dipole arrays)

Crossed-loop antennas with Watson-Watt evaluation (Fig. 8) are mainly suitable for mobile applications due to their compact size. They feature the following benefits and drawbacks:

- Benefits: minimum signal duration is sufficient, simple implementation, little space required
- Drawbacks: small-aperture system ($D/\lambda<0.2$) leading to errors in case of multipath propagation, large DF errors in case of skywaves with steep elevation angles

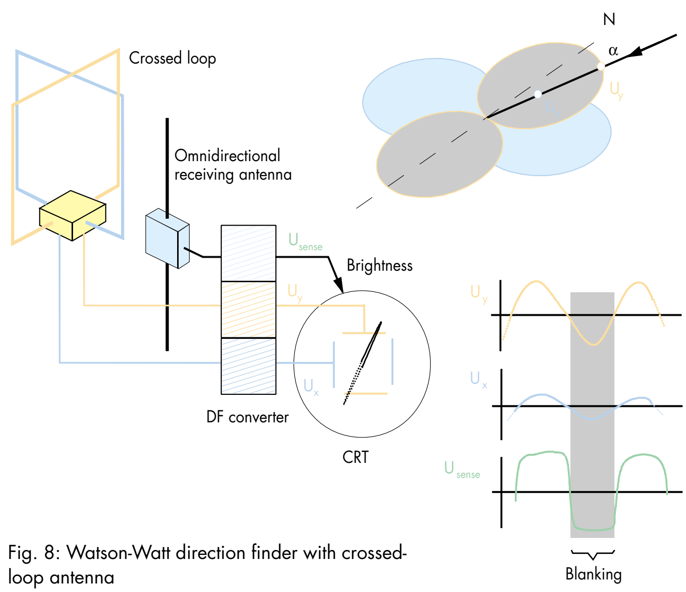

Fig. 8: Watson-Watt direction finder with crossed-loop antenna

Adcock antennas (Fig. 9) feature the following advantages over crossed-loop antennas:

- Improved error tolerances for sky-wave reception
- Implementation of wider apertures to avoid errors in case of multipath reception (eg $D/\lambda<1$ for 8-fold Adcock)

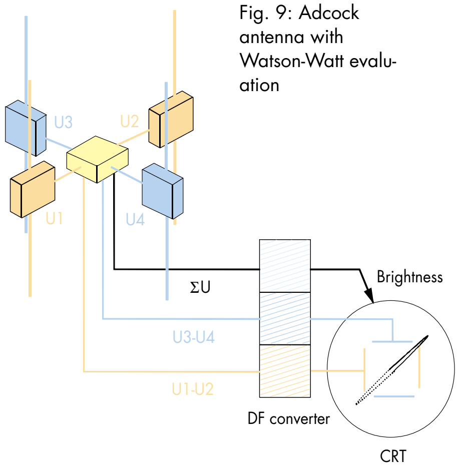

Fig. 9: Adcock antenna with Watson-Watt evaluation

The main selectivity is effected with the aid of digital filters; the bearings are calculated numerically, eg from the last equation above and displayed on a computer with graphical user interface (workstation, PC).

A number of disadvantages of analog direction finders can be avoided in this way:

- Synchronization of channels also on filter edges
- Simple method of considering correction values for antenna networks, cables, etc
- No temperature drift in digital section
- Bearings are available in numeric form for further evaluation, in particular for easy transmission to remote evaluation stations

Fig. 11: Digital direction finder (above) and Adcock DF antenna (below)

Modern direction finders no longer display the IF voltages of the antenna signals on a CRT, but digitally process the signals simultaneously in a relatively wide IF band (Fig. 10).

Fig. 11 shows a direction finder using digital signal processing which evaluates the signals of the Adcock antenna shown below according to the Watson-Watt principle.

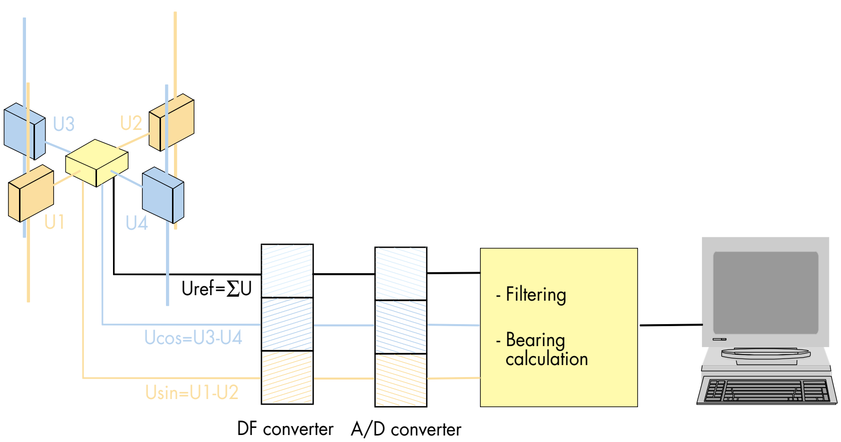

Fig. 10: Configuration of a modern direction finder according to the Watson-Watt principle

3.3 Doppler direction finder

If an antenna element rotates on a circle with the radius R, the received signal with the frequency ω_0 is frequency-modulated with the rotating frequency ω_r of the antenna due to the Doppler effect: if the antenna moves towards the radiation source, the frequency is increased; if the antenna moves away from the radiation source, the receive frequency is reduced.

From the instantaneous amplitude

$$u(t)=a\cos\left(\omega_0 t+\frac{2\pi R}{\lambda_0}\cos(\omega_r t-\alpha)+\varphi\right)$$

the instantaneous frequency is derived by differentiation

$$\omega(t)=\frac{d\phi(t)}{dt}=\omega_0-\frac{2\pi R}{\lambda_0}\omega_r\sin(\omega_r t-\alpha)\ .$$

After filtering out the DC component $\omega_{0,}$ the demodulated Doppler signal is obtained as

$$S_D = \frac{2\pi R}{\lambda_0}\,\omega_r \sin(\omega_r t - \alpha)\ .$$

The phase of the demodulated signal compared to a reference signal of equal center frequency derived from the antenna rotation yields

$$S_r = -\sin \omega_r t$$

the bearing α.

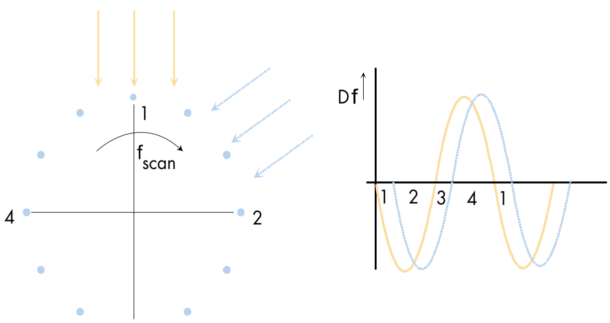

Fig. 12: Principle of Doppler direction finder

Since mechanical rotation of an antenna element is in practice neither possible nor recommendable, several elements (dipoles, monopoles, crossed loops) are arranged on a circle (Fig. 12) and electronically scanned with the aid of electronic switches.

To obtain unambiguous DF results, the spacing between the individual antenna elements must be smaller than half the operating wavelength; in practice a distance of about one third of the minimum operating wavelength is usually selected. Fig. 13 shows an example of a Doppler direction finder for portable use in the frequency range 20 MHz to 1000 MHz.

If this rule is adhered to, Doppler DF antennas of any size can be made so that wide-aperture systems featuring

- high immunity to multipath reception and
- high sensitivity

can be implemented in a simple way.

A disadvantage of the Doppler method is the time required, since at least one antenna scanning cycle is needed to obtain a bearing. With a typical rotating frequency of 170 Hz in the VHF/UHF band one cycle takes about 6 ms.

3.4 Interferometer

The interferometer direction finder determines the angle of incidence of a wave by directly measuring the phase difference between the signals picked up at different points on the received wavefront by the elements of the antenna array (Fig. 14).

Unambiguous determination of the azimuth and elevation with the aid of three antenna elements is only possible if the spacing a between the antennas is not greater than half a wavelength. If Φ_1, Φ_2, Φ_3 are the phases measured at the antenna element outputs, the azimuth is calculated as

$$\hat{\alpha} = \arctan \frac{\Phi_2 - \Phi_1}{\Phi_3 - \Phi_1}\ .$$

The elevation angle is obtained as

$$\hat{\varepsilon} = \arccos \frac{\sqrt{(\Phi_2 - \Phi_1)^2 + (\Phi_3 - \Phi_1)^2}}{2\pi a/\lambda}\ .$$

In practice, the 3-antenna configuration is usually enhanced by further antenna elements so that the antenna spacings can be optimally adapted to the operating frequency range and antenna spacings of $\alpha > \lambda/2$ be used


Fig. 13: Doppler direction finder for portable use in frequency range 20 MHz to 1000 MHz

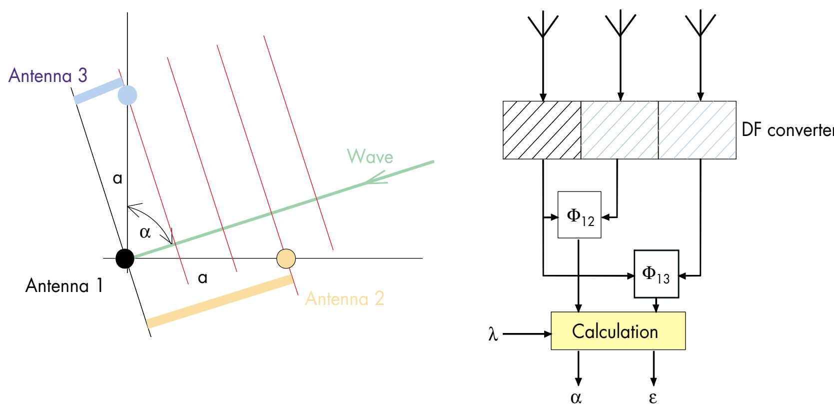

Fig. 14: 3-element interferometer

to increase the accuracy of small-aperture DF systems. Frequently used antenna arrangements include the right-angled isoceles triangle and the circular array (Fig. 15).

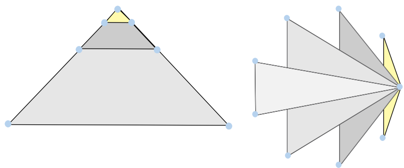

Fig. 15: 3-element interferometer enhanced to form a multi-element interferometer

Triangular arrays are usually restricted to frequencies below 30 MHz. At higher frequencies it is recommended to use circular arrays since these

- ensure equal radiation coupling between the antenna elements as well as
- minimum coupling with the antenna supporting mast and
- due to the symmetry about the center point favour direction-independent characteristics at different positions.

Special considerations are to be given to avoiding ambiguities that result from the fact that unambiguous measurement of the phase is only possible in the range of ±180°. As already mentioned before, the spacing between the elements of a 3-element (small-aperture) interferometer is therefore limited to half the minimum operating wavelength. For multi-element interferometers there are the following possibilities:

- **Use of "filled" antenna groups:** phase differences between neighbouring elements are always smaller than 180°; ambiguities can thus be avoided
- **Use of "thinned out" antenna groups:** at least one neighbouring pair of elements with a phase difference >180°

There are the following approaches to resolve ambiguities:

- Coarse direction finding using a small-aperture system ($\alpha<\lambda/2$)
- Use of circular arrays with at least one antenna pair having a phase difference of less than 180°

Fig. 16: Direction Finder DDF06M (photo 42136) operating on the principle of a correlative interferometer for the frequency range 20 MHz to 3000 MHz. Nine antenna elements are used for each of the three frequency subranges (photo 43073-2)

A very effective means of eliminating the ambiguities of thinned out circular arrays is the correlation method.

Fig. 16 shows a direction finder designed according to the correlation principle. The antenna array covers the frequency range 20 MHz to 3000 MHz.

The basic principle of the **correlative interferometer** entails a comparison of the measured phase differences with those obtained for a DF antenna system of known configuration at a given wave angle. The comparison is made by calculating the quadratic error or forming the correlation coefficient of the two data sets. If different azimuth values of the comparison data set are used, the bearing is obtained from the data for which the correlation is at a maximum.

This is illustrated by the example of a 5-element antenna as shown in Fig. 17: each column of the lower data matrix corresponds to a wave angle α and forms a comparison vector. The elements of the comparison vectors represent the expected phase differences between the antenna elements for this direction of incidence. The upper 5x1 data matrix contains the currently measured phase differences (measurement vector).

To determine the unknown direction of incidence each column of the lower reference matrix is correlated with the measurement vector by multiplying and adding the vectors element by element. The result is the correlation function $K(\alpha)$, which reaches its maximum with the optimum coincidence of comparison vector and measurement vector. The angle associated with the comparison vector is the wanted bearing.

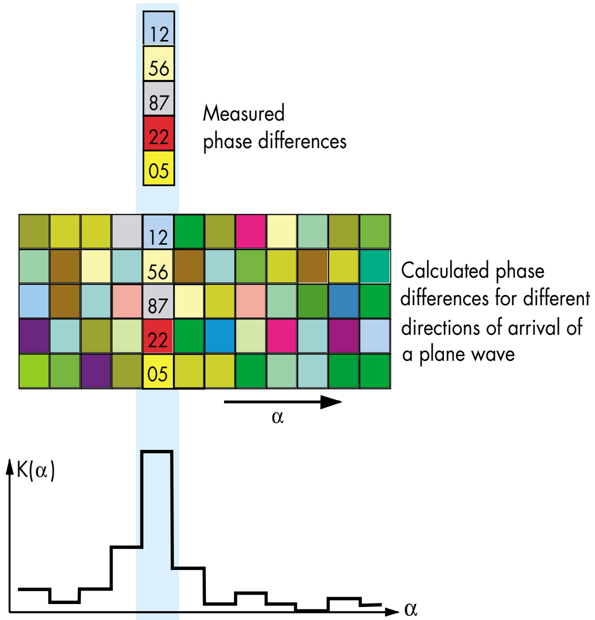

Fig. 17: Principle of correlation evaluation

This method is a special form of a beamforming algorithm [11], which is described in detail in the following section on direction finding using sensor array processing.