finder to the electronic visual direction finder. As from 1943 British naval vessels were equipped with crossed loops and three-channel Watson-Watt direction finders for the shortwave range ("huff-duff" for detecting German submarines).

As from 1931 camouflaged direction finders were available for use in vehicles and as portable direction finders for detecting spies.

The first shortwave direction finder operating on the Doppler principle was built in 1941. The rapid progress in the development of radar in Great Britain made it necessary to cover higher frequency ranges: in 1943 the first direction finders for "radar observation" at around 3000 MHz were delivered.

As from 1943 wide-aperture circular-array direction finders (Wullenweber) were built for use as remote direction finders. Since the 1950s, airports all over the world have been equipped with VHF/HF Doppler direction finding systems for air-traffic control.

In the early 1970s, digital technique made its way into direction finding and radiolocation; digital bearing evaluation and digital remote control are the main outcomes of this development.

As from 1980 digital signal processing has been increasingly used in direction finding. It permits the implementation of the interferometer direction finder and initial approaches towards the realization of multiwave direction finders ("super resolution"). The first theoretical considerations were made much earlier, eg in [4].

Another important impulse for the development came from the requirement for direction finding of frequency-agile emissions such as frequency-hopping and spread-spectrum signals. The main result of this development was the broadband direction finder which is able to simultaneously carry out the search and DF process on the basis of digital filter banks (usually with the aid of **F**ast **F**ourier **T**ransform) [5].

### 1.3 Tasks of radio direction finding

The task of a radio direction finder is to estimate the direction of an emitter by measuring and evaluating electromagnetic field parameters.

Usually the **azimuth** $\alpha$ is sufficient to determine the direction; measurement of the **elevation** $\varepsilon$ is of interest for emitters installed in flying platforms and especially for direction finding of shortwave signals (Fig. 2).

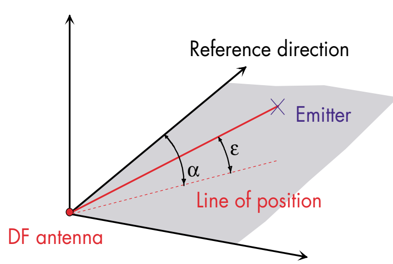


Fig. 2: Definition of emitter direction

Only in the case of undisturbed wave propagation is the direction of the emitter identical with the direction of incidence of the radio waves. Usually there is a large number of partial waves arriving from different directions and making up a more or less scattered field. The direction finder takes from this wavefront spatial and temporal samples and supplies in the ideal case the estimated values $\hat{\alpha}$ and $\hat{\varepsilon}$ for the most probable direction of the emitter observed.

The bearing can be referred to the following reference directions (Fig. 3) (see also DIN 13312 [6]):

- True north (true radio bearing)
- Magnetic north
- Vehicle axis or relative radio bearing

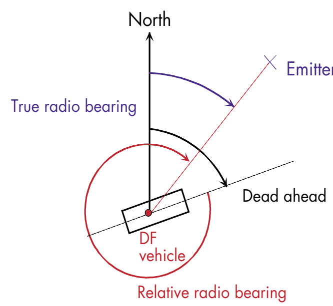


Fig. 3: Reference directions

## 2 DF Principles

### 2.1 Generation and characteristics of electromagnetic waves

Electromagnetic waves are caused by charging and discharging processes on electrical conductors in the form of AC currents [7], [8].

The first assumption is based on an undisturbed propagation of a harmonic wave of the wavelength $\lambda$. At a sufficiently large distance the radial field components are largely decayed so that limited to a small area the wave can be considered to be plane: electric and magnetic field components are orthogonal and in-phase to each other and perpendicular to the propagation direction which is defined by the **radiation density vector (Poynting vector)** $\vec{S}$

$$\vec{S} = \vec{E} \times \vec{H} = \vec{e}_0 \frac{|E|^2}{Z_0}$$

where E = effective value of electric field strength

$Z_0$ = characteristic impedance of free space; $Z_0 \cong 120\pi\Omega$

or by the **wave number vector** $\vec{k}$

(Fig. 4). $$\vec{k} = \vec{e}_0 \frac{2\pi}{\lambda}$$

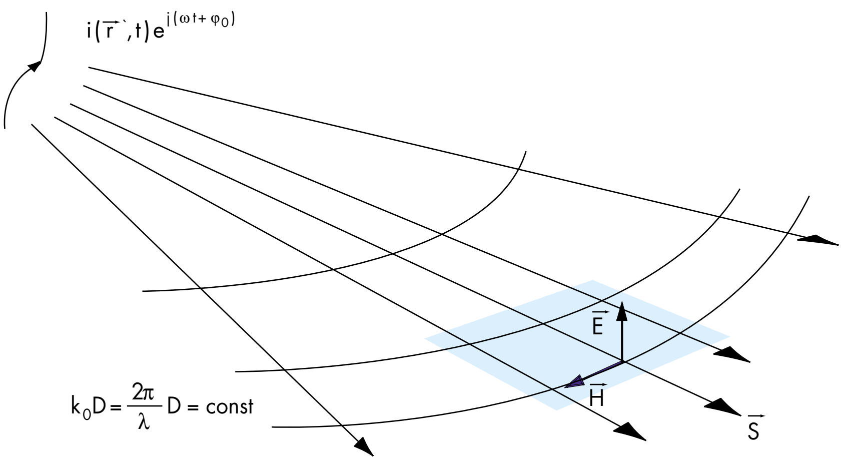


Fig. 4: Propagation of space waves

| Wave characteristic | Transversality | Phase surfaces ⊥ Direction of propagation | | |
|---|---|---|---|---|
| **DF principle** | **Polarization direction finder** | **Phase direction finder** | | |
| | | **Direction finding with directional patterns** | **Aperture sampling** | |
| | | Conversion phase –> amplitude | Direct evaluation | Sensor array processing |
| **Examples** | - Rotating loop<br>- Dipole<br>- Loaded loop<br>- Crossed loop with Watson-Watt evaluation | - Directional antenna Maximum signal direction finder Minimum signal direction finder<br>- Adcock with Watson-Watt evaluation | - Interferometer<br>- Rotating field direction finder<br>- Doppler direction finder | - Correlation direction finder<br>- Adaptive beam former<br>- MUSIC<br>- ESPRIT |

Table: DF principles

## 2.2 Overview of the main DF principles

The basic characteristics of electromagnetic waves, ie

- transversality (field vectors are perpendicular to direction of propagation) and
- orthogonality of phase surfaces and direction of propagation

form the foundation of radio direction finding. Any DF process can be traced back to one of the following two methods (see Table):

- Method A: measuring the direction of electric and/or magnetic filed vectors (polarization direction finders)
- Method B: measuring the orientation of surfaces of equal phase (or lines of equal phase if the elevation is not of interest) (phase direction finder)

**Polarization direction finders** are implemented by means of dipole and loop antennas. The classical rotating-loop direction finder belongs to this category (rotation of loop to minimum received signal → direction of wave incidence perpendicular to loop). Nowadays polarization direction finders are used in situations where there is sufficient space only for small antennas, eg in vehicles and on board ships for direction finding in the HF band. Evaluation is usually made according to the Watson-Watt principle (Chapter 3).

**Phase direction finders** obtain the directional information from the spatial position of the lines or surfaces of equal phase. There are two basic methods:

- **Direction finding with directional characteristics:**
  With this method partial waves are coupled out at various points of the antenna system and combined at one point to form a sum signal. The maximum of this sum signal occurs at that antenna angle at which the phase differences between the partial waves is at a minimum. The sum signal is thus always orthogonal to the phase surfaces of the incident wave (maximum-signal direction finding). For minimum-signal direction finding the partial waves are combined so that the phase differences in the direction of the wave incidence become maximal and there is a distinct minimum of the received signal
- **Direction finding by means of aperture sampling:**
  With this method, samples are taken at various points of the field and applied to sequential or parallel evaluation circuits which determine the bearing by subjecting the samples to predominantly mathematical operations.
  Interferometers, rotating-field direction finders and Doppler direction finders are typical examples.
  The DF methods mentioned so far are suitable to a limited extent only for determining the directions of incidence of several overlapping waves in the frequency domain. With the progress made in digital signal processing the methods known from the theory of spectral estimation have been applied to the analysis of wavefronts and further developed. The term "sensor array processing" describes the technique of gaining information about the parameters of the incident waves from the element signals of sensor arrays (antenna arrays in radio direction finding, hydrophone arrays for sonar).
  There are basically two different methods:
  – Beamforming methods, eg correlation direction finder, spatial Fourier analysis, adaptive antenna
  – Subspace methods, eg MUSIC, ESPRIT

## 2.3 Requirements on DF systems

The main requirements are:

- High accuracy
- High sensitivity
- Sufficient large-signal immunity
- Immunity to field distortion caused by multipath propagation
- Immunity to polarization errors
- Determination of elevation in shortwave range
- Stable response in case of non-coherent co-channel interferers
- DF of short-duration
- Scanning direction finders: high scanning speed and probability of intercept (POI)

## 2.4 Components of a DF system

A DF system (Fig. 5) consists of the following components:

- antenna system
- DF converter
- evaluation unit and
- display unit

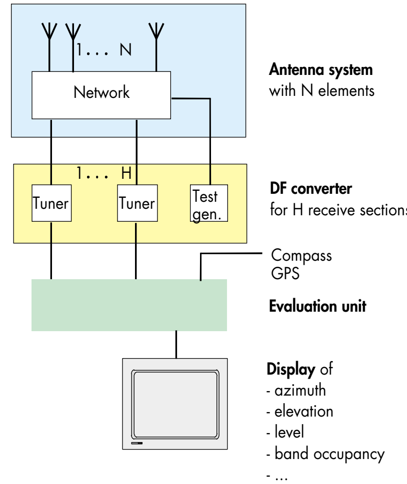


Fig. 5: DF system components

Depending on the configuration, systems for determining the DF's own coordinates/orientation (GPS, compass), remote-control units (LAN, WAN), antenna control units, etc, can be added.

The achievable DF speed mainly depends on the number H of receive sections which determines the number of antenna outputs measured in parallel.

To achieve maximum speed it must be possible to obtain the bearing in one time step, ie from one set of samples (monopulse direction finding). For unambiguous direction finding over the total azimuth range at least three antenna outputs are required. If there are also three receive sections, multiplexing of the measurement channel is not required.

Typical examples of monopulse DF antennas are:

- 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.