Chapter 2

Essentials

A brief description of the fundamentals of remote sensing of precipitation by means of radar measurements will be given in the first section of this chapter. Subsequently, the products of the BALTEX radar centre BRDC will be introduced.

2.1 Fundamentals

Many publication deals with the fundamentals of radar meteorology. This is the reason, why this section is comparatively short and will introduce only the most important terms, as far as they are indispensable for the understanding of this study. For a more substantial description I wish to refer to basic literature, such as the books of Atlas (1990) and Battan (1973).

Precipitation is a generic term for water in solid or liquid form that falls from the sky as part of the weather to the earth's surface. The precipitation amount, that falls to surface is indeed a two-dimensional representation of a three-dimensional reality above ground. Precipitation in appreciable amounts can be produced by two basic types of mechanism. One is the spontaneous (or free) lifting of humid air, and the other is the forced lifting of humid air. Spontaneous rise are associated with strong up-drafts within convection cells. Free lifting is associated with frontal systems.

Radar The term "radar" originally stands for **R**adio **A**ircraft **D**etection **a**nd **R**anging. This points to the first task of radar in its history, the detection of aircrafts for military use. Atmospheric hydrometeors interfered the beam frequently, so that the possible benefit for meteorological use was quickly recognised. General speaking, radar is a system, that uses radio waves for positioning of targets in the atmosphere. The realisation is done by a system of two components usually combined in the antenna, the emitter and receiver of pulsed energy.

Table 2.1: Radar band letter nomenclature and corresponding wavelengths and frequencies.

Band Designation	Nominal Wavelength	Nominal Frequency	Appropriate meteorological scatterers
L	30-15 cm	1-2 GHz	
S	15-8 cm	2-4 GHz	large precipitation droplets
C	8-4 cm	4-8 GHz	precipitation
X	4-2.5 cm	8-12 GHz	precipitation and cloud droplets
K_u	2.5-1.7 cm	12-18 GHz	small precipitation and cloud droplets
K	1.7-1.2 cm	18-27 GHz	cloud droplets
K_a	1.2-0.75 cm	27-40 GHz	cloud droplets
V	0.75-0.4 cm	40-75 GHz	cloud droplets
W	0.4-0.27 cm	75-110 GHz	small cloud droplets (up to 95 Ghz)

Backscattered energy with the corresponding runtime of a radar pulse give the link to target scatterers.

A particularly worthwhile enhancement of radar technique is the use of the Doppler shift to analyse fall speed (Lhermitte and Atlas, 1963) and radial velocity (Donaldson, 1970) of the particles. This technique allows among others an improved clutter identification as well as a retrieving of wind components. Radars, those can measure polarisation differences can examine the shape of raindrops. Some techniques (i.g. Zhang et al. (2001)) use those information for a better determination of the relation between radar reflectivity and rainfall at the surface.

Radar band letter nomenclature The wavelength regions of weather radar can be broadly divided into seven different groups from the L-Band to W-band (see Table 2.1). In radar meteorology it is supposed, that the hydrometeors satisfy the condition of Rayleigh Approximation, so that the chosen wavelength λ of the emitted radar beam should be approx. 10 times bigger than the droplet diameter. That means, that rain droplets of a diameter of 5 mm can be sufficiently measured up a wavelength of approx. 5 cm in the C-band. In fact, most of weather radars work in X-band, C-band or S-band. S-band antenna requires large antenna and, therefore are mechanically undesirable and relatively expensive. X-band are well suited to observe small precipitation particle as well as cloud droplets. However, radar beams in the X-band are not able to penetrate heavier precipitation. While S-band instruments are the standard in North America, European radar stations usually measure in C-band.

Radar equation The basic physical equation of radar meteorology is the *radar equation*. It includes a transformation of the received energy value in the reflectivity factor Z, the basic physical unit of radar meteorology. Detailed derivations can be found in each textbook about radar meteorology (e.g. Battan (1973), Atlas (1990), Sauvageot (1992), Sauvageot (1994)). For a volume of a number n of scatterers with a size s the radar equation can be written as

$$P_r = \frac{P_t G^2 \lambda^2}{(4\pi)^3 r^4} \mathrm{d}V \int n(s)\sigma(s)\mathrm{d}s \tag{2.1}$$

where P_r denotes the power received by the radar, P_t is the transmitted power, G is the gain of the antenna, λ is the transmitted radar wavelength, σ is the backscattering cross section of a single scatterer and r the distance from transmitter to the target. P_r is expressed in unit W. Considering the geometry of the radar beam the volume dV is

$$\mathrm{d}V \approx \frac{\pi R^2 \phi \psi c \tau}{8} \tag{2.2}$$

where ϕ and ψ are the half-power beam widths expressed in radiance. The length of the emitted pulse $c\tau$ can be referred to as the radar resolution.

Eq. 2.1 is the general radar equation for all imaginable targets and applications, such as for aircrafts, surfaces and also raindrops.

Radar equation for Rayleigh assumption To come to a specific radar equation for meteorological use it is assumed that the atmospheric targets act as Rayleigh scatterers. That means the scatterers are considerably smaller than the wavelength of the radar beam. Then the cross section σ of meteorological targets is proportional to the sixth power of diameter D:

$$\sigma(r) = \frac{\pi^5}{\lambda^4} |K|^2 D^6 \tag{2.3}$$

where $|K|^2 = |\frac{\varepsilon - 1}{\varepsilon + 2}|^2$ includes the dielectric constant ε, that strongly depends on the phase of the particle.

The radar reflectivity factor Z is defined as the integral over the 6th power of all drop diameter within a volume:

$$Z = \int n(D) D^6 dD \tag{2.4}$$

where $n(D)$ is the number of droplets with a diameter between D and $D + dD$. Substitution of Eqs. 2.3 and 2.4 in Eq. 2.1 and summarising the constants and the specific radar parameters (G, λ, $\Delta\phi$,$\Delta\nu$, h and P_t in Eq. 2.1) for any individual radar in a constant C the radar equation for meteorological use can be written as:

$$P_r = C\frac{|K|^2}{r^2}Z \tag{2.5}$$

As mentioned before, different mixtures of phases for atmospheric water have a wide range of values for $|K|^2$ (Stephens (1994)):

Water	$|K|^2 = 0.93$
Ice	$|K|^2 = 0.176$
95% Ice, 5% Water	$|K|^2 = 0.39$
70% Ice, 30% Water	$|K|^2 = 0.78$
Dry snow	$|K|^2 = 0.208$

It can be seen that the change from the solid to the liquid phase leads to an increase of backscattered energy of more than a factor of four. This phenomena and the different fall velocity of liquid and solid water particle lead to the "bright band", a vertical layer with particular large radar echoes.

The radar reflectivity factor Z has dimensions of $\mathrm{mm}^6\mathrm{m}^{-3}$ and provides the link between radar measurements and precipitation intensity. It is common to express Z in terms of decibels (dBZ) due to the large range of possible values of Z, e.g 10^{-2} to 10^7 $\mathrm{mm}^6\mathrm{m}^{-3}$. The radar reflectivity factor Z_{dBZ} is defined as

$$Z_{dBZ} = 10\log_{10}\frac{Z}{Z_0} \tag{2.6}$$

Thus, $Z(dBZ)$ measures the relation in reflectivity from any Z to a reference value $Z_0 = 1\ \mathrm{mm}^6\mathrm{m}^{-3}$

The raindrop size distribution is given by an inverse exponential function, the well-known Marshall-Palmer relation (Marshall and Palmer, 1948):

$$n(D) = N_0 e^{-\lambda D} \tag{2.7}$$

where $n(D)$ is the number of droplets in the size range D to $D + dD$. In the fundamental study of Marshall and Palmer (1948) N_0 was assigned for stratiform precipitation as a value of 8000 m^{-3} mm^{-1}. The parameter λ is given by empirical relations, such as

$$\lambda = 4.1R^{-0.21} \tag{2.8}$$

for rain (Gunn and Marshall, 1958) and

$$\lambda = 2.29R^{-0.45} \tag{2.9}$$

Table 2.2: Radar reflectivity factor Z and corresponding rain intensity.

Rainfall Caterogy	dBZ	Rain Intensity
mist to light	15-30 dBZ	0.2-2 mm
moderate	30-40 dBZ	2-10 mm
heavy	40-46 dBZ	10-30 mm
very heavy	46-50 dBZ	30-50 mm
intense	50-56 dBZ	50-100 mm
extreme (hail)	56-60 dBZ	over 100 mm

for snow (Sekhorn and Srivastava (1970)). The value R represents the rain rate expressed in millimetres per hour (mm/h).

If one combine Eq. 2.7 and Eq. 2.4 a relation of radar reflectivity and droplet diameter size is obtained:

$$Z = N_0 \int_0^\infty e^{-\lambda D} D^6 dD \tag{2.10}$$

The relation between Z and the rain rate R, referred as to Z-R relation, can be derived by the Marshall-Palmer (Eq. 2.7) distribution with a formulation of the rain rate as the vertical integral over mass density.

$$R = \frac{1}{\rho_l} \int_0^\infty n(D) m(D) D^3 \nu dD \tag{2.11}$$

where the rain rate R is typically measured in millimetres of rain per hour (mm/h) and ρ_l is the mass density of the water. The insertion of $n(D)$ and the assumption that the droplet velocity acts as $\nu = aD^b$ provides the well-known form of the Z-R relation

$$Z = aR^b \tag{2.12}$$

The Z-R relation is in fact strongly influenced by the raindrop size distribution. So, it is easily understandable that there can not be an universal relationship between received radar reflectivity and precipitation at surface. The natural variability in the occurrence of different types of precipitation is mirrored in the wide range of assumed parameters for a and b as shown in Table 2.1.

Eq. 2.5 is in reality an approximation, since other factors can modify the radar beam. The most important factors are:

- Only partially or inhomogeneously filled radar pulse volume
- The possibility of mixed water phases of the target particles.

- The effects of multiple scattering

These error sources has to keep in consideration by interpretation of radar images.

Table 2.3: Coefficients a and b in some typical Z/R relations of the form $Z = aR^b$ for various rainfall types

Source	Precipitation type	a	b
Joss and Waldvogel (1990)	Stratiform	300	1.6
Rosenfeld et al. (1993)	Tropical Rain	250	1.2
Marshall and Palmer (1948)	Stratiform	200	1.6
Fujiwara (1965)	Thunderstorm	486	1.37

2.2 The radar data set BALTRAD

The data used for this study are the composite images from the BALTEX radar network BALTRAD compiled at the Baltex Radar Centre (BRDC). The BRDC has been established at the Swedish Weather Service (SMHI) for collecting data from as many precipitation radars in or adjacent to the Baltic Sea catchment area as possible, deriving homogenous data sets, distributing them to BALTEX data users, and archiving the data sets. The products are outlined in Michelson et al. (1999) and presented in detail in Michelson et al. (2000); Michelson and Koistinen (2000).

BALTRAD consists of more than 30 weather radars in Norway, Sweden, Denmark, Germany, Poland and Finland. Most of the radar instruments have Doppler functionality and operate in the C-Band (at 5 cm wavelength), while two radars operate in the X-band (at 3 cm wavelength). BALTRAD data products include radar reflectivity images of each of the individual radar stations, composite images of radar reflectivity factor and images for three and twelve hour accumulated precipitation sums. Rain rate products are derived by additional adjustment techniques employing rain gauge measurements. Measurements and initial Cartesian map representation for the individual radar are carried out by the national weather services of the contributing countries. Before composites can be generated, they must be transformed to a common data format, data grid and reflectivity factor interval. The 2D representations within the national weather services are mostly a Pseudo-CAPPI (CAPPI is referred to as *Constant Altitude Plan Position Indicator*) scheme. CAPPI includes only radar measurements which are obtained by observations at a specified altitude. Pseudo-

CAPPI, in contrast, can be seen as "CAPPI, if it is possible" and otherwise the closest thing to the CAPPI altitude. While values close to radars are obtained by measurement volumes below the CAPPI altitude, information from a range of more than 150 km comes from upper levels. The CAPPI altitude in the BALTRAD data set lies at 500 metres.

Figure 2.1: Domain of BALTRAD radar network with acronyms for radar stations (from Michelson et al., 2000)

BALTRAD composite images, designated as Composite Images of Radar Reflectivity Factor DBZC, are produced with a spatial resolution of 2 km, a temporal resolution of 15 minutes as an 8-bit data array. The value limits range from -30 dBZ to 72 dBZ. That corresponds to a information depth resolution of 0.4 dBZ. The data array consists on 815 x 1195 picture elements. Geographical projection type is an azimuthal equal area Lambert projection. The coordinates of corner points are 6.748°degrees longitude and 47.478°degrees latitude for the lower (south) left (west) and 36.243°degrees longitude and 69.172°for the upper (north) right (east) corner. If more than one radar observe a vertical column the value with lowest distance to the earth's surface is chosen for this pixel. The radius of ray curvature is considered by the calculation of the closest beam to surface.

A novel ground clutter removal technique was applied by BRDC. Comparison of 2-meter surface temperature by Mesoscale Analysis system (MESAN) with temperature information of a IR sensor channel aboard the METEOSAT satellites group is used to reject radar echoes, if the difference exceeds a threshold of ΔT =20 Kelvin. The resulting DBCZ images are distributed by the radar centre to data user via CD-ROM.

Two correction algorithms have to be applied by the user before further proceedings: Firstly, a preliminary adjustment scheme for each radar instrument are examined to balance different radar's electrical calibration levels according to:

$$Z_{ck} = Z_{org} + F_r \tag{2.13}$$

where Z_{org} is the original reflectivity factor, Z_{ck} is a preliminary reflectivity factor after radar specific calibration adjustment and F_r is the radar-specific correction coefficient ranging from 2.7 dBZ for radar Arlanda to 11.7 dBZ for Lulea. These values were provided by BRDC and found through comparison of gauge rain rates with those of radar. The coefficients were determined for a long-term period and changed only once in the three-year period of this investigation. It was necessary to apply the adjustment scheme of Eq. 2.13 for each pixel in each slot for the corresponding radar site, because not each radar instrument was used in each slot. The next adjustment step is specified for six hour periods. A gauge-radar adjustment technique provides coefficients to fit the reflectivity patterns to surface measurements of precipitation rates. In this process, a correction of systematic range-dependent biases are also embedded. The adjustment is carried out with

$$Z_{cor} = Z_{ck} \cdot 10^{c_0 + c_1 r + c_2 r^2} \tag{2.14}$$

where Z_{cor} is the corrected reflectivity, c_i are the coefficients provided by BRDC and r is the distance of each pixel to the next radar site. The distance r in unit km must be calculated for each slot and pixel, because not all radar instruments worked through the entire period. To give an example, the coefficients for 12.March 2000 12:00 UTC are $c_0 = -0.234560$, $c_1 = -1.6 \cdot 10^{-3}$ 1/km, and $c_2 = 34.49 \cdot 10^{-6}$ 1/km^2, so that Z_{ck} is multiplied with 0.893541 for pixels with a distance of 100 kilometres to the next radar for adjustment.

For the purpose of this study and in accordance with Michelson et al. (2000), instantaneous and corrected composite images of the radar reflectivity factor Z (unit dBZ) were converted to two-dimensional precipitation images containing rain rate R (in mm/h) using a standard Marshall-Palmer relation $Z = aR^b$ with $a = 400,\ b = 2$ for cold season (October to March) and $a = 200,\ b = 1.6$ for warm season (April through September).

When using ground based radar data, serious complications arise, especially using quantitative rain rates. The high sensitivity of rain intensity to errors in radar reflectivity factor result in a high uncertainty in any instantaneous rain rate. Further, despite several carefully applied correction algorithms for ground clutter, beam blocking, and anomalous propagation (Michelson et al., 2000), inhomogeneities and errors in accumulated precipitation maps generated from this dataset - as well as from any other dataset based on ground based weather radar - can also not be completely avoided. Those uncertainties have to be accounted for in uncertainty estimates that go along with the described method.

The radar data composites used in this study cover 95% of the Baltic Sea and about 75% of the catchment.Two isolated radars (over Poland) had to be excluded from the investigation because the missing overlap with the other radar prevented any spatial analysis on data taken from those radars. Three years of data - from January 2000 to December 2002 - were used for the development and application of the methodology.