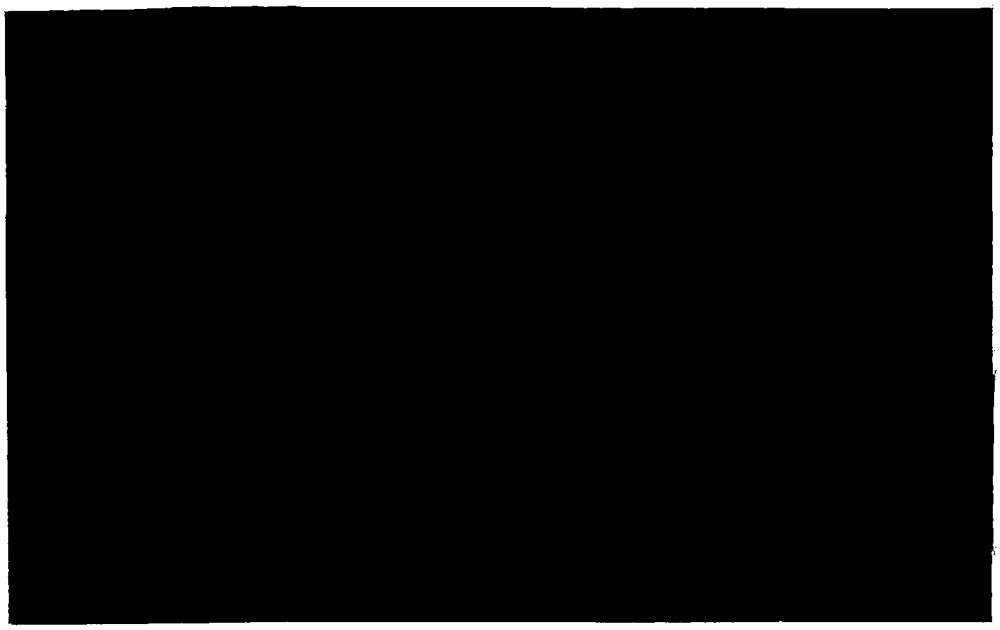

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PRECIPITATION MEASUREMENT AND HYDROLOGY

by

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Summary

Good agreement between radar and raingauges is found close to radar sites (13 % error for 6 hours of integration in a well defined catchment area) but strong variability and underestimation by radar occurs at longer ranges. The better of the two Swiss radars sees on the average only 25 % of the rain - in spite of the fact, that it measures 100 % close to the radar (Sec. 4.6) - because of earth curvature or shielding by topography (Sec. 3.1). Similar, but not quite so dramatic results are found in flat country. In other words, the main problem of using radar for precipitation measurements and hydrology in operational applications comes from the inability to measure precipitation close enough to the ground. Because of the fact that this problem is hardly detectable in well defined experiments, it did not receive the attention in the past which it deserved as a dominant problem in operational applications at longer ranges. Thanks to the availability of inexpensive, high speed data processing equipment, it is possible today to determine the echo distribution in the whole radar coverage area in three dimensions (full volume scan). It is this new knowledge together with the knowledge about the position of the radar and the orography around it, which will allow us to correct in real time for a large fraction of - or at least estimate - these errors. This correction will permit us to extend the region, in which a good accuracy is obtained, an accuracy known to us from todays well defined experiments and acceptable for many hydrological applications. To make the best possible use of radar, it may be useful to consider the following rules:

1. Precipitation shall be estimated immediately over the ground. If this is not possible, which will be the case e.g. at longer ranges, the values have to be corrected for errors originating from the vertical profile of reflectivity (Sec. 2.4). As this profile changes in time it has, for best results, to be measured continuously by the radar and the correction has to be calculated for each pixel knowing the height of the lowest visible volume above the ground (Sec. 6.1).
2. It is important that this correction, being the dominant one at longer ranges, is done before any other useful adjustments are applied: Estimating Z-R relationships with various methods, taking into account advection, adjustment with raingauges, etc (Sec. 3.7).
3. A radar site is chosen such that precipitation close to the ground is seen by the radar (Sec. 3.5). Seen means here, that there is no shielding or clutter (Sec. 3.1) or that the influence of clutter can be eliminated e.g. by Doppler analysis (Sec. 6.2). This condition may frequently restrict the useful range of radar for quantitative work to the nearest 50-100 km.
4. Rigorously controlled systems are used (sufficient stability and calibration of equipment, Sec. 3.6)
5. Wavelength and antenna size are reasonable: Negligible attenuation caused by precipitation (Sec. 3.2) and good spatial resolution, e.g. with a 1-degree beam (Sec. 3.4) are required.
6. The data are integrated over a number of hours and/or square kilometers, i.e. adequate sample size is provided. Integration has to be done over the desired quantity (e.g. the linear rain rate, not the log (Z)) in order to avoid any bias caused by this integration (Sec. 3.3).

Even a crude estimate of the actual vertical reflectivity profile will bring an important improvement, an improvement not obtainable with other means such as polarisation and multiwavelength techniques. Here the question is open, whether the additional cost and complexity of such techniques justify the gain for operational applications in hydrology. Research has to continue and to show how these new methods have to be used in operational applications and what advantage will result. A speculation of the expected improvement of different techniques to reduce the variance of radar to estimate rain at the ground is given in section 7.2.

Good quantitative information is already being obtained form radars, if we consider, that rain rates are estimated over a wide range between 0.1 and over 100 mm/h. We should not forget, however, that the main advantages of radar are in the high spatial resolution, the area coverage and its immediacy (real-time data), the capability to follow a "floating target or a convective complex" in a real-time-sequence - e.g. to make a short term forecast - and that it is only to a lesser degree suited to give absolute accuracy in measuring rain amounts. It is therefore unlikely that radar will ever replace the raingauge, raingauges being essential for adjustment and checking e.g. by comparing daily amounts. On the other hand, as pointed out by many workers, one would need an extremely dense and costly network of gauges to obtain a resolution easily attainable with radar. Furthermore there is no such easy way to get information about the vertical development of precipitation as with radar.

Zusammenfassung

In kurzer Entfernung vom Radargerät findet man eine gute Uebereinstimmung zwischen Niederschlagsmessungen mit Radar und Regenmessern, z.B. 13 % Fehler für 6-stündliche Niederschlagsmengen in einem wohldefinierten Experiment. In grösserer Entfernung vom Radargerät dagegen nimmt die Variabilität des Messfehlers zu und die Niederschlagsmenge wird vom Radar unterbewertet. Beispielsweise sieht das bessere der beiden schweizerischen Radargeräte im Mittel im ganzen Erfassungsbereich nur 25 % der Niederschlagsmenge am Boden, dies trotz der Tatsache, dass es im Nahbereich 100 % anzeigt, (Sec. 4.6). Dafür sind tote Zonen verantwortlich, die durch Bodenechos von Bergen und Abschattung durch Erdkrümmung und Berge bewirkt werden. Aehnliche Resultate, allerdings nicht so ausgeprägt, findet man im Flachland. In anderen Worten, das Hauptproblem der Niederschlagsmessung mit Radar für hydrologische Anwendungen liegt in der Unfähigkeit, den Niederschlag genügend nahe über dem Boden zu messen. Da dieses Problem in wohldefinierten Experimenten (kurze Entfernung vom Radargerät) nur schwierig festzustellen ist, hat es in der Vergangenheit nicht die ihm gebührende Beachtung erhalten. Dank der Verfügbarkeit von preisgünstigen Rechnern mit grosser Leistung, ist es jedoch heute durchaus möglich, das ganze dreidimensionale Niederschlagsvolumen abzutasten. Diese neue Information, zusammen mit dem Wissen um das Gelände und die Position des Radargerätes werden uns in Zukunft erlauben, diese Fehler zu einem grossen Teil zu korrigieren oder wenigstens ihre Grössenordnung abzuschätzen. Diese Korrektur wird es uns gestatten, den Erfassungsbereich des Radargerätes zu erweitern und eine Genauigkeit zu erreichen, wie sie uns von den wohldefinierten Experimenten her bekannt ist und die für viele hydrologische Anwendungen akzeptabel ist. Um den bestmöglichen Nutzen aus Radardaten zu ziehen, sind folgende Punkte zu beachten:

1. Der Niederschlag muss vom Radargerät unmittelbar über dem Boden erfasst werden. Falls dies nicht möglich ist, was beispielsweise in grösseren Entfernungen zutreffen wird, müssen die Werte mit Hilfe der lokalen Sichtbarkeit und dem vertikalen Echoprofil korrigiert werden (Sec. 2.4). Da dieses Profil sich im Verlauf der Zeit ändert, muss es für beste Resultate kontinuierlich abgeschätzt werden. Die Korrektur muss für jedes Pixel aufgrund der minimalen Erfassungshöhe und der Höhe der Erdoberfläche erfolgen (Sec. 6.1).

2. Da diese Korrektur in grösserer Entfernung dominant ist, muss sie vor allen anderen angebracht werden, beispielsweise vor solchen, welche angebracht werden, beispielsweise vor solchen, welche auf den verschiedenen Methoden beruhen, die Z-R Beziehung abzuschätzen, oder solche, die die Windadvektion oder eine Angleichung an Niederschlagsmesser berücksichtigen (Sec. 3.7).

3. Der Radarstandort wird so gewählt, dass der Niederschlag möglichst nah über dem Boden gesehen werden kann (Sec. 3.5). Gesehen heisst hier, dass keine Abschattung oder Bodenechos auftreten (Sec. 3.1) oder dass Bodenechos eliminiert werden können, z.B. durch Dopplerauswertungen (Sec. 6.2). Diese Bedingung wird den nutzbaren Radarbereich vielfach auf 50-100 km Entfernung beschränken.

4. Es werden einwandfreie Geräte verwendet (genügend Stabilität der Hardware und Eichung im Unterhalt, Sec. 3.6).

5. Wellenlänge und Antennengrösse werden vernünftig gewählt: vernachlässigbare Abschwächung durch Niederschlag (Sec. 3.2) und gute örtliche Auflösung, z.B. mit einer 1-Grad Antenne (Sec. 3.4).

6. Die Daten werden über einige Stunden und/oder Quadratkilometer integriert, d.h. eine sinnvolle Stichprobengrösse ist gewährleistet. Die Integration muss über die uns interessierende Grösse erfolgen, z.B. über die lineare Niederschlagsmenge und nicht über Log(Z), dies damit systematische Abweichungen wegen der Mittelung vermieden werden (Sec. 3.3).

Bereits eine grobe Abschätzung des aktuellen vertikalen Reflektivitätsprofils wird eine wesentliche Verbesserung bringen, eine Verbesserung, die mit anderen Mitteln, wie verschiedener Polarisationsrichtungen oder Wellenlängen, nicht erreicht werden können. Bei allen diesen Mitteln bleibt heute die Frage offen, ob der erreichbare Nutzen für hydrologische Anwendungen den Aufwand und die zusätzliche Komplexität der Einrichtungen rechtfertigt. Auf diesen Gebieten muss die Forschung fortgesetzt werden und zeigen, wie diese neuen Verfahren operationell angewendet werden sollen und welches ihr Gewinn sein wird. Im Kapitel 7.2 werden Spekulationen darüber angestellt, welche Verbesserungen die verschiedenen, vorgeschlagenen Verfahren bringen können.

Bereits heute - ohne diese raffinierten Mittel - erhalten wir vom Radargerät wertvolle Informationen, wenn man bedenkt, dass wir damit Niederschlagsintensitäten im Bereich von 0.1 bis über 100 mm/h erfassen. Jedoch sollten wir nicht vergessen, dass die Hauptvorteile von Radar in seiner hohen örtlichen Auflösung, im grossen erfassbaren Gebiet, in der Möglichkeit, ein "bewegtes Ziel ausfindig zu machen oder einen konvektiven Komplex" zu verfolgen, - z.B. für die Kurzfristprognose - liegen, und dass das Radargerät im Grunde genommen weniger geeignet ist, mit hoher Genauigkeit Niederschlagsmessungen zu bestimmen. Es ist daher unwahrscheinlich, dass Radar je die klassische Niederschlagsmessung verdrängen wird. Diese wird weiterhin zur Kontrolle notwendig sein, z.B. mittels Vergleichs von täglichen Niederschlagssummen. Andererseits, wie von vielen Autoren betont, müsste ein Netz von Niederschlagsmessern extrem dicht sein und würde grosse Kosten verursachen, wenn dieses die gleiche örtliche und zeitliche Auflösung aufweisen soll, wie es mit Radar relativ einfach zu erreichen ist. Zudem gibt uns Radar einzigartige Möglichkeiten, die vertikale Entwicklung von Niederschlägen zu erfassen.

Sommario

Tra la precipitazione rilevata a breve distanza dal radar e quella misurata dai pluviometri è stata osservata una buona concordanza (13 % di errore per 6 ore di integrazione in un'area di misura ben definita), ma anche molta variabilità e sottoestimazione da parte del radar a distanze più elevate. Il migliore dei 2 radar svizzeri (Albis) vede in media solo il 25 % delle precipitazioni, - sebbene esso misuri il 100 % in prossimità (Sez. 4.6) - a causa dell'occultazione dovuta alla topografia e alla curvatura terrestre (Sez. 3.1). Simili risultati, sebbene non così drammatici, sono stati ottenuti in regioni pianeggianti. In altre parole, usando il radar per misurare precipitazioni e per applicazioni idrologiche operazionali, il problema principale è causato dall'incapacità di misurare le precipitazioni in prossimità del terreno. Poichè questo problema, dominante nelle applicazioni operazionali a largo raggio, si manifesta difficilmente in esperimenti ben definiti, in passato non gli fu dedicata sufficiente attenzione. Grazie ai costi ridotti e all'efficienza degli elaboratori elettronici, è possibile oggigiorno determinare in tre dimensioni la distribuzione degli echi su tutta l'area di coper-

tura del radar (tutto il volume d'esplorazione). E' questa nuova cognizione, unitamente a quella relativa alla posizione del radar e all'orografia che lo circonda, che ci permetterà di correggere in tempo reale una gran parte, o almeno di stimare questi errori (Sez. 6.1). Tale correzione ci darà modo di estendere la regione nella quale si ottiene una buona accuratezza, - conosciuta oggigiorno quale risultato di esperimenti ben definiti - e nello stesso tempo accettabile per una gran parte di applicazioni idrologiche.

Onde poter usufruire in modo ottimale del radar, sarà utile considerare le regole seguenti:

1. La precipitazione deve essere stimata direttamente al disopra del suolo. Qualora ciò non sia possibile, - il che sarà il caso p.es. a lunga distanza - i valori dovranno essere corretti dagli errori originati dal profilo verticale di riflettività (Sez. 2.4). Per ottenere buoni risultati, dato che il profilo cambia nel tempo, esso deve venir misurato continuamente dal radar e la correzione calcolata per ogni pixel conoscendo l'altezza del volume visibile localizzato il più vicino possibile al suolo.
2. E' importante che questa correzione, essendo dominante a distanze elevate, sia effettuata prima di ogni altro utile adattamento quali la stima della relazione Z-R con vari metodi, la presa in considerazione dell'avvezione, la registrazione mediante pluviometri, ecc. (Sez. 3.7).
3. Locazione del radar scelta in modo che sia visibile la precipitazione in prossimità del suolo (Sez. 3.5). Visibile vuole indicare qui l'assenza di ostacoli o echi fissi (Sez. 3.1) o che l'influsso di questi ultimi possa venir eliminato, per esempio mediante analisi Doppler (Sez. 6.2). Queste condizioni possono spesso restringere il raggio utile del radar per valutazioni quantitative a circa 50 - 100 km.
4. Uso di sistemi controllati rigorosamente (sufficiente stabilità e calibrazione dell'equipaggiamento, Sez. 3.6).
5. Lunghezza d'onda e dimensione dell'antenna ragionevoli: trascurabile attenuazione dovuta alle precipitazioni (Sez. 3.2), e buona risoluzione spaziale, per esempio con un'apertura del raggio di 1 grado (Sez. 3.4).
6. Integrazione dei dati su di un numero sufficiente di ore e/o chilometri quadrati (scelta adeguata del campionamento). L'integrazione deve venir effettuata sulla quantità desiderata (per esempio la quantità lineare di precipitazione e non il logaritmo della riflettività) per evitare ogni errore sistematico causato da tale integrazione (Sez. 3.3).

Anche una cruda stima dell'attuale profilo di reflettività verticale darà un miglioramento importante, un contributo non ottenibile con altri mezzi quali ad esempio le tecniche di doppia polarizzazione o di lunghezze d'onde multiple. Resta aperta la questione se il costo addizionale e la complessità di tali tecniche giustifichino o meno il miglioramento ottenibile in applicazioni idrologiche operazionali. La ricerca deve continuare e mostrare come queste nuove tecniche siano da usarsi per applicazioni operazionali e che vantaggio ne risulterà. Una speculazione sulle migliorie ottenibili mediante l'apporto di differenti tecniche, onde ridurre la varianza delle misure radar per la stima di precipitazione al suolo viene presentata nella sezione 7.2.

Attualmente otteniamo già una buona informazione quantitativa dal radar se consideriamo che la quantità di precipitazione è stimata su di un'ampia gamma - tra 0.1 e più di 100 mm orari -. Non dobbiamo tuttavia dimenticare, che i maggiori vantaggi del radar sono l'alta risoluzione spaziale, l'area di copertura e la sua immediatezza (valori in tempo reale), la capacità di seguire "un obiettivo fluttuante o un complesso convettivo" in una sequenza in tempo reale, per esempio farne una previsione a breve termine, e che solo in piccola parte è adatto a fornire misurazioni della quantità di precipitazione con alta accuratezza. E' perciò improbabile che il radar possa sostituire il pluviometro, essendo questo uno strumento essenziale per la rettifica ed il controllo, ad esempio mediante confronto dei quantitativi giornalieri. D'altra parte, come già accennato in molti altri lavori, sarebbe necessaria una rete molto densa e costosa di pluviometri per raggiungere una risoluzione facilmente ottenibile con il radar. D'altronde non esistono tuttora altre vie così facili come con il radar per ottenere informazioni sullo sviluppo verticale delle precipitazioni.

Résumé

Les mesures des précipitations exécutées à l'aide de pluviomètres et déduites des observations au radar présentent de bonnes concordances, quand la distance, séparant le champ de précipitation et le radar, est courte (13 % d'erreur pour 6 heures de précipitation sur une surface bien définie). A grande distance on observe en revanche une forte variabilité de l'erreur, les mesures au radar étant sous-estimées. Par exemple, le meilleur des deux radars suisses ne donneil en moyenne que 25 % de la quantité de pluie au sol sur l'ensemble du domaine de prospection, bien que les 100 % soient atteints dans le domaine proche (Sec. 4.6). Les raisons en sont les zones mortes, provoquées par les échos dûs au relief (montagne), et par l'"ombre" portée par la courbure de la terre et par les montagnes (Sec. 3.1).

On trouve des résultats analogues sur le plateau, mais à vrai dire moins prononcés. En d'autres termes, le problème principal de la mesure des précipitations à l'aide du radar pour les applications hydrologiques, réside dans l'incapacité de mesurer les précipitations suffisamment près du sol. Comme ce problème est difficilement détectable dans des expériences bien définies (proche du radar), il n'a pas reçu toute l'attention voulue dans le passé. Grâce à la disponibilité de calculateurs bon marché à grande capacité, il est aujourd'hui possible d'explorer dans les 3 dimensions l'ensemble du volume de précipitation. Cette nouvelle information, liée à la connaissance du relief et à la position du radar, permettront à l'avenir de corriger en grande partie cette erreur, ou du moins d'en évaluer l'ordre de grandeur. La correction permettra d'élargir le domaine de prospection du radar et d'atteindre une exactitude comparable à celle correspondant aux domaines proches et acceptable pour des nombreuses applications hydrologiques. Pour tirer le meilleur parti des données radars, les points suivants sont à considérer:

1) Le radar doit saisir les précipitations directement au-dessus du sol. Si, en raison de l'éloignement trop grand des précipitations, cette condition n'est pas remplie, les valeurs obtenues doivent être corrigées selon la visibilité locale et le profil vertical des échos (Sec. 2.4). Comme ce profil varie avec le temps, il doit être évalué de manière continue pour obtenir le meilleur résultat. La correction doit se faire pour chaque Pixel, sur la base d'une altitude minimale de prospection et pour le volume visible le plus bas au-dessus du sol (Sec. 6.1).

2) Comme cette correction est dominante à grande distance, il est important qu'elle soit exécutée avant tout autre ajustement utile, par exemple, avant celui qui s'appuit la relation Z-R déterminée par plusieurs méthodes ou, avant les ajustements qui tiennent compte de l'advection du vent ou un rajustement au pluviomètre (Sec. 3.7).

3) On choisira l'emplacement du radar de telle façon que les précipitations soient visibles aussi près du sol que possible (Sec. 3.5), c'est-à-dire sans apparition de phénomènes d'"ombre" ou d'échos dûs au sol (Sec. 3.1), ou que ces derniers, à la rigueur, pouvant être éliminés, entre autres, par analyse Doppler (Sec. 6.2). Cette condition limite souvent le domaine de prospection utile du radar à 50 - 100 km.

4) On utilisera un appareillage irréprochable (stabilité suffisante du Hardware et étalonnage au cours de l'entretien, Sec. 3.6).

5) Choix convenable de la longueur d'onde et des dimensions de l'antenne: Atténuation négligeable par précipitation (Sec. 3.2) et bonne résolution spatiale, par exemple, avec un faisceau de un degré d'angle (Sec. 3.4).

6) Les données sont intégrées sur quelques heures et/ou sur une surface de plusieurs kilomètres carrés, ce qui revient à dire que les dimensions adéquates de l'échantillonnage sont garanties. L'intégration se fait sur la grandeur désirée, par exemple, sur la quantité linéaire des précipitations et non sur le logarithme de la réflectivité, ceci pour éviter des écarts systématiques occasionnés par l'intégration (Sec. 3.3).

Une estimation grossière du profil vertical de la réflectivité, en temps réel, apporte déjà une amélioration capitale, irréalisable avec d'autres moyens, comme, par exemple, avec les techniques de double polarisation ou des longueurs d'ondes multiples. La question reste ouverte, de savoir si le profit atteint pour les applications hydrologiques justifie l'ampleur financière et la complexité technique des installations. La recherche doit être poursuivie dans ce domaine et montrer comment ces nouveaux procédés peuvent être utilisés dans la pratique et quels en sont leurs avantages. Dans le dernier chapitre sont exposés des spéculations pouvant apporter des améliorations aux procédures proposées.

Aujourd'hui déjà, la technique du radar donne de précieuses informations, si l'on songe que l'intensité des précipitations, comprise entre 0,1 et 100 mm/h ou plus, peut être estimée. Il ne faut cependant pas oublier que l'avantage primodial du radar provient du fait de sa grande résolution spatiale dans un vaste domaine de prospection, de sa possibilité de suivre "une cible mouvante ou un paquet d'air convectif" (par exemple pour les prévisions à court terme). En revanche, il ne faut pas non plus ignorer que le radar est en principe moins qualifié pour déterminer avec exactitude les quantités de précipitations. Il est par conséquent peu probable qu'il supplante un jour les mesures classiques des précipitations. Ces dernières continueront à servir de contrôle, par exemple au moyen des totaux journaliers. Par ailleurs, comme souligné par maints auteurs, le réseau des pluviomètres devrait être si dense que les coûts seraient énormes pour obtenir une même résolution spatiale et temporelle que celle obtenue relativement facilement avec le radar. En plus, le radar fournit la seule possibilité de saisir le développement vertical des précipitations.

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"Precipitation Measurement and Hydrology", a Review

by

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1 INTRODUCTION

1.1 Fundamentals

The most striking advantage of using radar for precipitation measurements is the rapid access to data in real time over a large area with high spatial and temporal resolution from a single point. Furthermore, we can obtain a three dimensional picture of the weather situation, which may be extended over a very large area by compositing data from several radars. Accuracies of the radar measurement of a few percent were obtained under favourable circumstances. This has tempted us in the past to assume that radar will provide good quantitative data of precipitation from the whole radar coverage area of the order of 400 km or more in diameter.

The basic principles of radar meteorology are well described in text books such as Atlas (1964), Kostarev et al (1971), Battan (1973) or Stepanenko (1973), or in WMO Reports such as Technical Note No. 78 (1966) on the "Use of Ground Based Radar" or Technical Note No. 110 (1970) "Use of Weather Radar for Aviation", and Technical Note No. 181 by C. Clift (1984) on the "Use of Radar in Meteorology". Therefore only a very brief summary will be given here.

The power received at the radar antenna from a precipitation field is proportional to the radar reflectivity Z and the radar constant C and is inversely proportional to the square of the distance d and to the attenuation A produced by rain and atmospheric gases:

$$P = (C/A)(Z/d^2) \qquad 1.1$$

The radar constant C depends on the transmitted power, the sensitivity of the receiver, the wavelength, the pulse duration, the beam width and the gain of the antenna. Beam width and gain depend on the radar wavelength and the size of the antenna: Short wavelength and/or large antennas produce a high gain and a narrow beam, both making it easier to measure weak precipitation at long ranges. This however is not the whole truth. In practice, as discussed by Smith (1986), attenuation and equipment considerations (availability and price) will also influence the optimal choice of the wavelength.

All particles of the precipitation field belonging to the sampling volume of the radar contribute to the radar return. Each particle contributes proportional to its back scattering cross section. The cross section is a function of the

wavelength of the radar, and the size, shape, orientation (if not spherical) and dielectric properties of the particle. The dielectric constant is very different for ice and water and varies with temperature. As long as particles are smaller than 1/3 of the wavelength (Rayleigh region of scattering, Battan 1973), the radar reflectivity Z is proportional to the 6th power of the diameter of the particles. The rainfall rate R is roughly proportional to the 4th power of the particle diameter. Therefore no unique relationship will exist between the radar reflectivity and the precipitation rate and this relationship must depend on the particle size distribution, which brings us to a first type of error, discussed in Sec. 2.1 to 2.3.

As we want to deduce the precipitation at the ground from a measurement sampled aloft, we make a second kind of error which is often not considered enough (Sec.2.4 and chapter 3). In chapter 3 we also find a third type of error related to instrumental considerations. Austin P.M. (1987) carefully discusses and illustrates the relative importance of these errors using case studies.

1.2 The Main Problem

Unfortunately precipitation at the ground is not necessarily directly related to the the radar reflectivity aloft, which may lead to difficulties. If the vertical reflectivity profile is sampled aloft, considerable underestimation of rainfall by radar may result. This problem is obvious in a mountainous country, but also in a flat country it may lead to unespectedly large errors. This is probably the main reason, why only little operational use has been made so far of reflectivity data for precipitation measurements, in spite of the fact, that in the past 40 years, radar has been proposed and investigated as a tool to measure rainfall quantitatively over a large area. Even worse, the comments made 1979 by Wilson and Brandes are still true: 'Both confusion and misunderstanding exist in the inherent ability of radar to measure rainfall, about factors that contribute to errors, and about the importance of careful calibration and signal processing'. The reason for this situation probably lies in the large variability of meteorological phenomena and applications. In other words, the fact that well defined field experiments gave remarkable agreement, does not necessarily imply that similar results can be obtained in operational applications over a larger area. This discrepancy can be explained by the fact, that in selected case studies at well defined ranges, some of the factors remain constant, whereas they otherwise may vary and contribute in a major way to the total error. However, these errors, if hidden in the radar-raingauge assessment factor (i.e. the correction factor obtained by dividing the rain amount obtained with calibrating gauges by the corresponding radar amount) of such limited experiments, will show up when the ideal conditions of such experiments are not fullfilled any more. They will produce unexpected deviations in operational applications and could finally be responsible for the lack of faith in radar as an operational tool to measure rainfall.

As discussed above, different sources of error become relevant depending upon the type of application. E.g. the distance between the radar and the region of interest, together with the type of storm, will determine whether errors because not detecting precipitation growing close to the ground (Sec.2.4 and 3.1) will be dominant or negligible as compared to errors originating from variations of the Z-R relationship or to an inaccurate radar calibration. In addition the type of question posed by the application will influence the relative importance of the different sources of error. E.g. the answer will be quite different when instantaneous values of the rain rate at a given location on the ground (raingauge) are required, than when daily amounts of rain over a river basin are of interest. In that case the raingauge itself may cause a sampling problem, and it is widely accepted that in such an application the raingauge is not well suited to investigate the error size of radar to measure rainfall. An overview

on these questions is given by Wilson and Brandes (1979).

2 PRECIPITATION

2.1 Particle Size Distributions (Rain, Snow, Hail)

Particle size distributions of raindrops, snowflakes and hailstones have probably been observed since the beginning of mankind. A very large interest in such distributions, mainly for raindrops, existed from the early days of radar meteorology, because they gave the possibility to deduce the Z-R relationship in a direct way (Sec.2.2). One of the first known measurements of raindrop size distributions is the one by Wiesner (1895), who used filter papers to catch the drops. This technique has been used by many groups since 1945 and is still in use in some places. The obvious advantage of the method is its simplicity, which has to be paid by a tremendous amount of effort for the evaluation. The situation has changed after 1970, when an electromechanical disdrometer was available (Joss and Waldvogel, 1967), which reduces the amount of work for obtaining a representative sample size.

The most widly used description of the size distributions of raindrops is that of Marshall and Palmer (1948), who found that the exponential shape fits measured raindrop spectra. In fact, the more averaging is done in time or space, the better the agreement with the exponential distribution will be (Joss and Gori 1978). Further investigations gave insights into the formation, development, variation and shape of raindrop size distributions. A large amount of studies about size distributions has been made for radar meteorological applications (Z-R relationships) as well as for cloud physical investigations. A summary about such work can be found in Battan (1973) or Pruppacher and Klett (1978); coalescence of raindrops (Srivastava, 1967); the breakup of raindrops (Low and List, 1982); the variation of raindrop spectra during storms (Waldvogel, 1974); the parametrisation and shape of raindrop size distributions (Joss and Gori, 1978; Ulbrich and Atlas, 1978), and finally the statistical problems one encounters when dealing with raindrop size distributions (Sec.3.3 or Cornford, 1967; Joss and Waldvogel, 1969; Gertzman and Atlas, 1977). A large amount of work has further been invested to fit measured raindrop spectra with better approximations than simple exponential distributions (Ulbrich, 1985), or by considering the very detailed shape of individual size distributions (Steiner and Waldvogel, 1987). Another investigation (Hoskins and Stow,1987) considers the arrival rate of raindrops at the ground. Although these studies give important aspects of parametrisation techniques for raindrop spectra or cloud physical interpretations of measured size distributions, these considerations are not of large importance for radar meteorological applications in hydrology (Sec.2.2).

Snowflake and hailstone size distributions did not get the same attention. This is true for the number of measurements made and reported as well as for the effort with which instruments have been developed. A review of surface hail instrumentation is given by Nicholas (1977). For snowflakes, only rudimentary techniques exist, see Ohtake (1970). Airborne instrumentation for drops, snowflakes and hailstones is using much more sophisticated techniques, see for instance Johnson and Smith (1980). However, this extremely useful instrumentation is not widely used in radar meteorology because of its large cost to operate it on an airplane. Therefore it is of great importance for research, that radar techniques are developed to give more information about particle size distributions.

The size distributions of snowflakes and hailstones are mostly also of the exponential type (Gunn and Marshall, 1958; Sekhon and Srivastava, 1970; Beckwith, 1960). The problem with snowflakes is their complex shape and

therefore the "diameter" normally corresponds to the melted waterdrop diameter. Hailstones also can have a complicated shape but here the maximum diameter is frequently taken, unless a scheme with some kind of parametrization is used to describe the shape of the hailstones (Wang et al 1987). Many investigators studied the backscattering behaviour of hailstones, especially in respect to new detection techniques (chapter 6). But again, for hydrological applications, there are more important aspects which have to be considered before; thus the simple approximation of spherical hailstones belonging to an exponential size distribution can be used without too large an error (Sec.5.8).

2.2 Z-R Relationship

In the past 40 years many authors have studied the variation of the Z-R relationships from storm to storm and within a storm (see Atlas, this volume). Various methods exist to estimate this relationship, e.g. by direct measurements of the drop size distribution (DSD) with a disdrometer (see previous section), by the radar itself using Doppler, multiparameter technique (see Chapter 6 or Bringi and Hendry, this volume) or by applying a climatology of precipitation types. A summary of empirical relationships are found by Battan (1973, p. 90).

Atlas et al (1984) review in great detail the possibilities for improving the remote measurement of rainfall by using drop size data only and analysing the error with which one can deduce the rain rate from an other variable or combination of variables. The result of this investigation can be illustrated with the absolute, average deviation of the rain rate calculated with one or several parameters from the distribution to the rain rate calculated directly from the same distribution. The result is given in %, 0% indicating perfect agreement:

	Variable(s)	Average deviation
Z	reflectivity	33%
Sigma	optical extinction	37%
A	attenuation	24%
Z,Sigma	reflectivity, optical extinction	8%
Z,A	reflectivity, attenuation	5%

Table 2.2: Error of estimate of rain rate calculated from various parameters, deduced from drop size data only (Atlas and Ulbrich, 1984).

When judging these numbers, we should keep in mind, that they are deduced from DSDs only and therefore indicate the best possible improvement obtainable under optimum conditions.
The authors find that empirical relationships involving optcal extinction and differential reflectivity of a polarisation diversity radar (ZDR) are sensitive to the shape of the DSD whereas those involving Z and A are not. Ulbrich and Atlas (1984) investigate therefore how much information about the shape of the DSD may be extracted from consideration of Z, extinction, and ZDR, and conclude, that 'the improvement may be important, provided complications caused by turbulence and windshear in the radar volume can be considered unimportant'.

Obviously the more information we know about the DSD and its shape, the better we can deduce rain rates. But the improvement we are discussing is at best some tens of percent. Whilst this is important, it is small compared to what is obtainable by considering the vertical profile of reflectivity discussed in Sec.2.4. In the first case (ZDR) a considerable effort in additional equipment is necessary, while in the second case (profile) only the scanning procedure of the antenna has to be modified and a software algorithm taking care of the vertical profile has to be implemented.

Following the original definition of the Z-R relationship the radar reflectivity factor Z and the rain rate R are best obtained from the drop size distribution. An alternative is to compare Z aloft with R on the ground. This procedure in fact includes errors originating from the vertical reflectivity profile in the Z-R relationship and therefore has to be specified as a function of altitude (Sec.2.4). The purely statistical approach for obtaining a Z-R relationship was proposed by Miller (1972) or by Calherios and Zawadzki (1981). Empirical relationships gained in this way may give insight into these questions and help to improve the accuracy of radar estimates. But on the other hand, if the assumptions of the analysis are not clearly stated, it may be confusing and is probably the reason for the fact that the relative importance of errors originating from the variation of the drop size distribution, whilst certainly important, are frequently overestimated; therefore we agree with Zawadski (1984) when he stated that 'the variability of drop-size spectra introduces one of many errors and not the most severe at that'. Multiparameter estimates of Z-R will never reduce errors caused by the vertical reflectivity profile, but at best the ones originating from the Z-R relationship in the classical sense. After some kind of averaging over time and/or space, these errors will rarely exceed a factor of 2 in rain rate and are, therefore, only dominant in well defined experiments and close to the radar. At longer ranges, even in flat country, errors caused by not seeing precipitation close to the ground are usually dominant. These may be more important and indeed be overlooked because of all the fascinating ways of determining and discussing distributions of drop size and Z-R relationships, being well defined problems, easy to grasp and therefore having received (too?) much attention in the past. Furthermore questions concerning the representativity in space and time and the influence of up- and down-drafts on the Z-R relationship, frequently remain open. But notable exceptions exist: E.g. Ulbrich (1986) investigating in detail the influence of down-drafts, or P.M. Austin (1987), analysing the results of 20 storms and discussing variation and value of Z-R relationships giving physical interpretations. She finds that natural variations of raindrop-size distributions appeared to be a significant factor in only two, relatively insignificant storms. She concludes therefore, that attempts to use multiparameter techniques for estimating Z-R 'tend to complicate the measurement without clearly improving the results'. Hail may cause a sharp increase of reflectivity. To avoid the resulting overestimation of rain rate, she proposes to limit the maximum value deduced from radar returns (e.g. to 100 mm/h for a 2 km and to 50 mm/h for a 4 km measurement cell).

2.3 Bright Band

A phenomenon frequently observed where snow is melting into rain is called the bright band. It may lead to a strong overestimate of precipitation by radar. Overestimates of up to a factor of 10 may be observed, provided that the radar has the necessary spatial resolution to identify the bright-band layer which has a typical thickness of the order of 300 m. Above the bright band, the reflectivity usually decreases rapidly. As most weather radars have sufficient spatial resolution only at close ranges, overestimation produced by bright-band enhancement occurs mainly near the radar. At medium ranges the bright band will compensate for the reduced reflectivity aloft and at longer ranges underestimation will dominate. Both errors, however, increase the variability of the assessment factor, making it more difficult to adjust a radar with a low density network of raingauges.

Many investigators studied cloud physical aspects of the bright band, see e.g. Atlas (1964), Leary and Houze (1979) whereas Collier (1986a) considers its influence on radar measured precipitation amounts. Barnes (1986) reports preliminary results of simultaneous radar, aircraft and satellite link data.

2.4 Vertical Reflectivity Profile, A Basic Problem In Radar Hydrology

Because of growth or evaporation of precipitation, air motion and change of phase (ice and water in the bright band), highly variable vertical reflectivity profiles are observed, both within a given storm and from storm to storm. On average, vertical reflectivity profiles show a decrease with height amounting to reflectivity gradients of up to 10 dB/km corresponding to a change of up to 16% of measured rain rate per 100 m, see Rogers and Yau (1981) or Joss et al (1974) for statistics, or Joss et al (1970) for sample profiles measured with a vertical-pointing radar, Schmid and Waldvogel (1986) for profiles containing hail or Koistinen (1986) for average profiles over a day. All these reflectivity gradients represent long-term averages only and instantaneous values may deviate strongly in both directions.

With increasing distance from the radar the vertical distance between the sample volume of the radar and the ground usually increases too, therefore the differences between estimates of rainfall by radar as compared to the raingauge must also increase. These differences consist mainly of underestimation by radar, but overestimation may also occur e.g. at short ranges in the bright band (Sec.2.3). At longer ranges, for smaller storms, and especially when low antenna elevations are blocked by obstacles (mountains), too little precipitation will be measured. This type of error will dominate all the others, a fact easily overlooked when investigating storms at close ranges only, or when analysing a similar type of storm always located at roughly the same range.

When estimating the vertical reflectivity profile with radar only (as usually is done), caution is needed. Five factors may lead to underestimation of the vertical gradient of reflectivity (i.e. the reduction of reflectivity with height), especially close to the ground. The contribution of each one will depend on the meteorological situation and the way of data analysis employed:

1. At low elevations part of the precipitation is not seen because of earth curvature and mountains or as it is eliminated by clutter suppression circuitry.

2. At longer ranges the sampling volume is not homogeneously filled with precipitation, the lower part containing usually the stronger echoes.

3. By choosing the radar echo itself as a criterion (instead of the precipitation at the ground) we introduce a bias, e.g. we may have echoes aloft and no precipitation at the ground.

4. We should average rain rates, not radar reflectivity. The latter leads to a bias, which depends upon the width of the distribution of averaged values (Sec.3.2).

5. When estimating the profile from the 3 projections of maximum reflectivity (as in the case of the Swiss display system, see Sec.4.5), a further bias is introduced.

We can avoid these problems and estimate the average vertical reflectivity profile, meaningfull for hydrologyical applications by investigating what the radar measures above raingauges, which are in such a position, that the corresponding volume is shielded by a known amount. This was done by Joss and Kappenberger (1984) for the storms which occured during the Special Observing Period of ALPEX in March and April 1982. The results of the information received by the two radars at La Dôle (near Geneva) and Albis (near Zürich) and by 46 raingauges are given in the following table.

Height of lowest beam [m]	Fraction seen by radar [%]	No. of gauges [-]	No. of storms [-]	Distance of gauges [km]	Height of gauges [m]
400-1000	33 (87) 208	10	20	15 (62) 158	437 (474) 570
1000-2000	58 (81) 129	7	16	11 (78) 155	316 (778) 1599
2000-3000	33 (54) 167	8	15	40 (75) 140	381 (947) 2490
3000-4000	3.3 (11) 22	5	14	69 (111) 208	482 (1421) 2282
4000-5000	1.0 (4.7) 18	7	14	86 (108) 135	640 (1626) 2690
5000-6000	0.5 (1.2) 2.7	2	3	98 (102) 105	1611 (1625) 1639
6000-7000	0 (0.1) 0.7	7	10	106 (133) 163	197 (1033) 3315

Table 3.1: (from Joss and Kappenberger, 1984): The fraction of precipitation (storm totals: radar-amount/raingauge-amount) seen by the radar is given in classes of the height of the lowest radar sample over the gauge. This height and the height of the gauges are indicated in meters above sea level. The distance of the radar from the gauge, the number of storms with a gauge-amount larger than 10 mm per storm and the number of gauges are also presented. If 3 numbers are given, they stand for the mimimum, (the mean) and the maximum value encountered. The height of the melting layer is at around 2000 m.

During the ALPEX period precipitation was mainly stratiform with a well pronounced bright band. In this case the apparent sensitivity of the radar (labled 'fraction seen') starts to decrease at the altitude of the bright band. As shown in the table, this occurs at first slowly (2 dB(R)/km) between 1500 and 2500 m) and then more rapidly (8 dB(R)/km between 4500 and 5500 m in this case). But other weather situations may be found where the decrease already starts below the bright band, even right above ground. The results show, that the reduction of sensitivity is clearly a function of blockage (in this case mainly reduced by shielding caused by mountains) and not because of distance or height of the ground (raingauge). Orographically induced growth of low level precipitation, as investigated by Collier et al (1983), may also be contribute.

Looking at the average vertical reflectivity profile measured with our radar in the above situation, we find that the maximum reflectivity averaged over the area of interest is at 3 km, with a strong reduction of sensitivity starting only at 5 km. This is in contradiction to the results above for the same data, but deduced from radar and raingauge data, which indicate that the maximum reflectivity is below 2 km (the height of the bright band) and that a strong decrease starts immediately above this level. The discrepancy between the two vertical reflectivity profiles (radar only and radar-raingauge) for the same situation is attributed to the 5 factors given above.

Physical reasons for the average decrease of reflectivity with height are discussed by Austin P.M. (1987). She concludes, that down-draft in heavy rain are often the dominant one. This seems to be reasonable, at least close to the ground. At higher levels growth by accretion is probably more important. In her Fig. 3 she finds a 3dB-reduction of Z (corresponding to 40% less rain rate) for a downdraft of 8 m/s.

2.5 Precipitation Fields, Representativeness

The structure of precipitation fields has been studied for a long time. Infact, radar meteorology is the discipline for investigating the scale between the synoptic phenomena and point observations which the individuum sees. The scale

in between, called mesoscale, has got a large interest in the last years, and gets today even increasing importance. Especially convective storms and mesoscale precipitation systems can be monitored now with great details and thus can help to avoid large damage. One of the early overviews about widespread precipitation fields is given by Harrold (1973) whereas Harrold and Austin P.M. (1974) discuss precipitation systems in general. The recent number of investigations about precipitation fields is so large, that a list of relevant references is not reasonable here. Therefore just two recent books are mentioned (Ludlam, 1980; Kessler, 1986) which can be used as an entrance to this broad field.

The representativeness of point measurements is another important aspect in connection with precipitation fields (Sec.3.3). It can be investigated with a very dense network of ground stations, often being used as a reference, but the effort is usually large and the use of radar data and models are frequently more elegant and complementary for studying this subject. Examples for model calculations are found in the papers by Silverman et al. (1981) and Gabriel (1981). They used models of elliptical rain cells with regularly and randomly located raingauges respectively. The results show the dependence of the accuracy of the measured amount of precipitation by the raingauges from the density of the network and the gradients within the rain cells. Waldvogel et al. (1982) study the representativeness of hailpad networks of different grid size with the help of radar data from 200 hail cells. Delrieu et al (1987) investigate several areal rainfall estimation methods including Thiessen's method, krieging and cokrieging. It becomes clear from these studies, that radar can be extremly useful for interpolating ground measurements from low density networks.

3 RADAR TECHNOLOGICAL PROBLEMS IN HYDROLOGY

3.1 Ground Clutter And Shielding

When the radar beam or its sidelobes encounter ground targets, strong persistent echoes will occur, which add up in time to large rain amounts if no precautions are taken in the data analysis. Fiore et al (1986) propose an automated system to detect and eliminate echoes from anomalous propagation by detecting cloudfree zones using VISSR sattellite data. Fortin et al (1987) give 3 criteria to recognise and eliminate clutter and even echoes coming from anomalous propagation. These can occur in locations, where under normal conditions no clutter is encountered. Here the strongest echoes will be found, when the radar beam travels horizontally along an inversion and produces large deviations from its normal propagation path. E.g. a vertical temperature gradient of 13 K/100 m or a vertical water-vapour pressure gradient of -3 hpa/100 m will deflect the straight beam into a circular path around the centre of the Earth. A deflection of the beam towards the ground is obtained therefore, when the air aloft is warm and dry compared to that below. This type of clutter is not easily eliminated. A rather crude method is to mask it by a clutter map in the computer memory as successfully in use in Switzerland since 1979. This clutter map, however, containing a bit of information for each pixel indicating whether it is clutter contaminated, leaves blind zones in clutter contaminated areas and leads to a loss of data. Because the clutter map has to be cumulated in many situations without rain, including those with anomalous propagation, this loss is larger in a given, single weather situation than it needs to be. Doppler techniques promise to reduce these difficulties in the spectral domain (Passarelli et al. 1981), although in areas prone to stationary orographic rainfall patterns, problems are likely to remain. For NEXRAD a clutter suppression of 30 dB is expected in the reflectivity channel (Golden et al, 1986). However little experience with the necessary algorithms for operational applications is available at present. In fact at the workshop (??) 1987 in England it was decided, that Doppler radar does not yet resolve the clutter problem. Gorgucci

et al (1986) investigate the possibility to use the 'Bias' between the logarithmically and linearly averaged signal to cancel ground echoes, but again little operational experience is yet available.

The curvature of the earth and topography may hinder the detection of important parts of the precipitation. As mentioned in Sec.2.4 this difficulty usually increases with increasing distance of the illuminated volume from the radar and is more severe in winter than in the warm season when the melting level is high. E.g. at 200 km, the lower limit of the radar beam is at about 3 km altitude, even in flat terrain. This may produce a significant underestimation of the rain rate or even lead to a complete lack of detection capability, especially for weak precipitation, which frequently grows at low levels. Fig. 3.1.1 presents the free percentage of volume (area unaffected by clutter or blockage) as a function of height of a radar at 500 m above sea level with an ideal horizon (no mountains). We find, that even in this ideal situation, using a 1 degree beam half of the useful area is shielded at an altidude of 3 km within a maximum range of 141 km. It is important to note, that in this ideal case, no echoes from the ground are received, they are removed by the immediate environement. Of course putting the radar on a tower or even on a mountain changes the situation drastically. This is demonstrated by Fig. 3.1.2, where at an average distance of around 100 km the free percentage of volume of radar La Dôle (Albis) in Switzerland is given as a function of height. The results show that depending on the height of the radar, clutter or shielding of precipitation are the dominant errors for quantitative measurement. To reduce this error, a higher radar site is better suited than a lower site, where the radar-shadows are more pronounced (Sec.3.5).

Most of the ground clutter may be eliminated by methods such as those discussed above, but beyond the location of the clutter blind zones will remain. In these zones the radar will never detect any rain. Provided these zones are small, a special algorithm for interpolation between precipitation echoes may be used (Galli 1984), but no remedy is possible for not being able to see precipitation behind the mountains or below the horizon, except the expensive solution to install more radars.

Sometimes we may even find echoes at long ranges in the shadow of the mountains or below the horizon. This can be caused by strong echoes reaching altitudes where they may be seen just by the top part of the main lobe of the radar beam or by side lobes when the centre of the main lobe is pointing at a height below the radar horizon, where the echoes are shown on the screen. Therefore, echoes are detected in the radar shadow in spite of the fact that the centre and the lower part of the main lobe is actually pointing into the mountains. The echoes are shown in the wrong place (i.e. below, to the left or to the right of the main beam axes), but this usually does not lead to crucial errors, because with these strong echoes aloft some echoes would be detected anyway below in the absence of the interferring topography. Note that at 200 km the diameter between 10-dB points (one way, and relevant to these offside echoes) of the main lobe of a 1 degree antenna is of the order of 7 km. In addition to the 3dB and 10 dB beam width table 3.1 gives the average height of the radar sampling volume and the reduction factor (radar/gauge) for various distances between radar and gauge, assuming an effective radius of the earth of 8000 km and a 1 degree beam at an elevation of 0.5 degree:

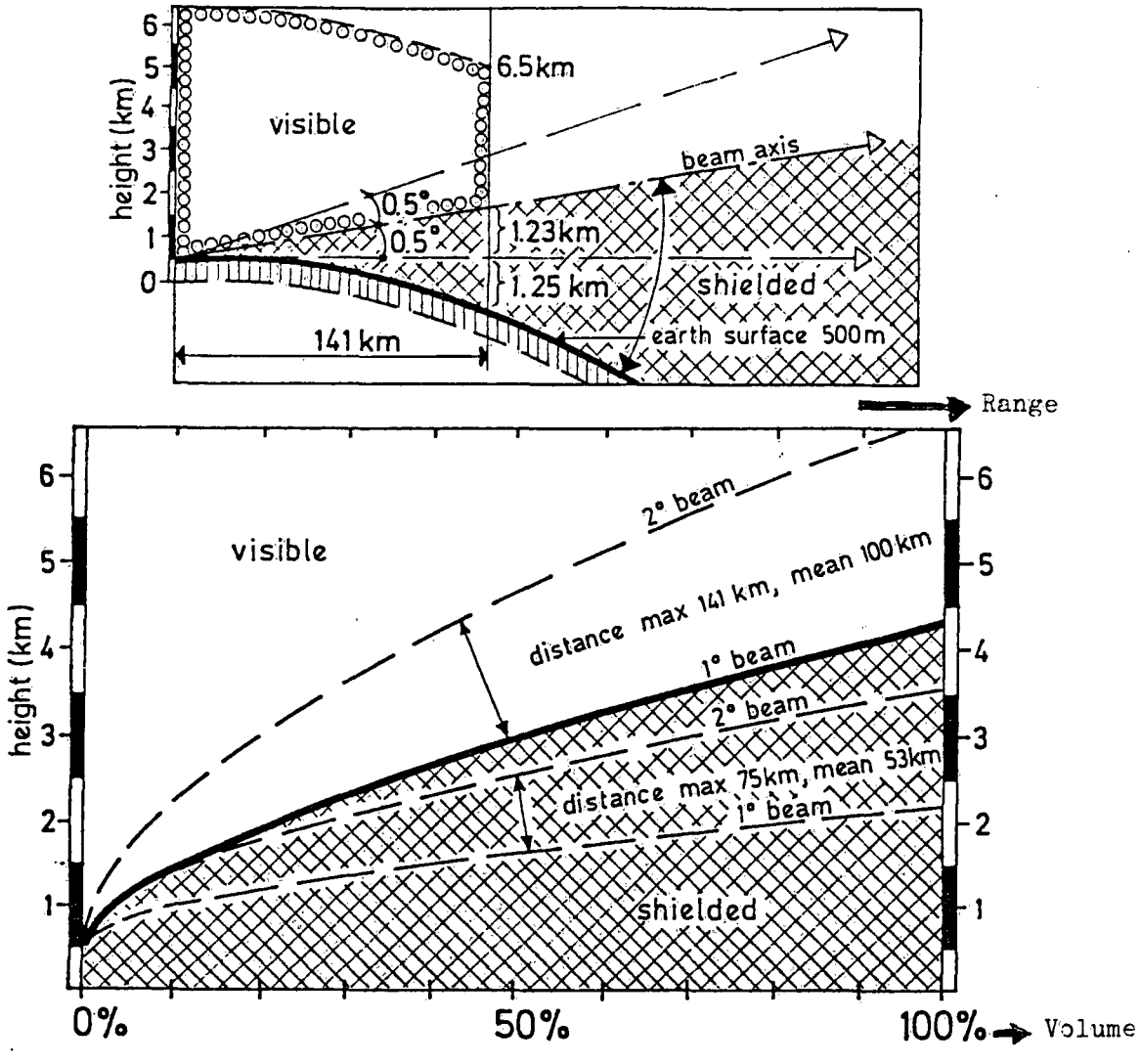


Fig. 3.1.1: Percentage of free volume as a function of the height for a radar at ground level, 500 m above sea with an ideal horizon (no mountains). It is assumed, that the lowest antenna elevation is set to half the beam width. Results are presented for 2 beamwidths (1 and 2 degree beam) and 2 ranges (75 and 141 km). We find, that even in this ideal situation using a 1 degree beam half of the usefull area is shielded at an altidude of 3 km within a maximum range of 141 km (average distance 100 km). It is important to note, that in this ideal case no echoes from the ground are received because they are removed by the immediate environment. Of course putting the radar on a tower or even on a mountain changes the situation drastically.

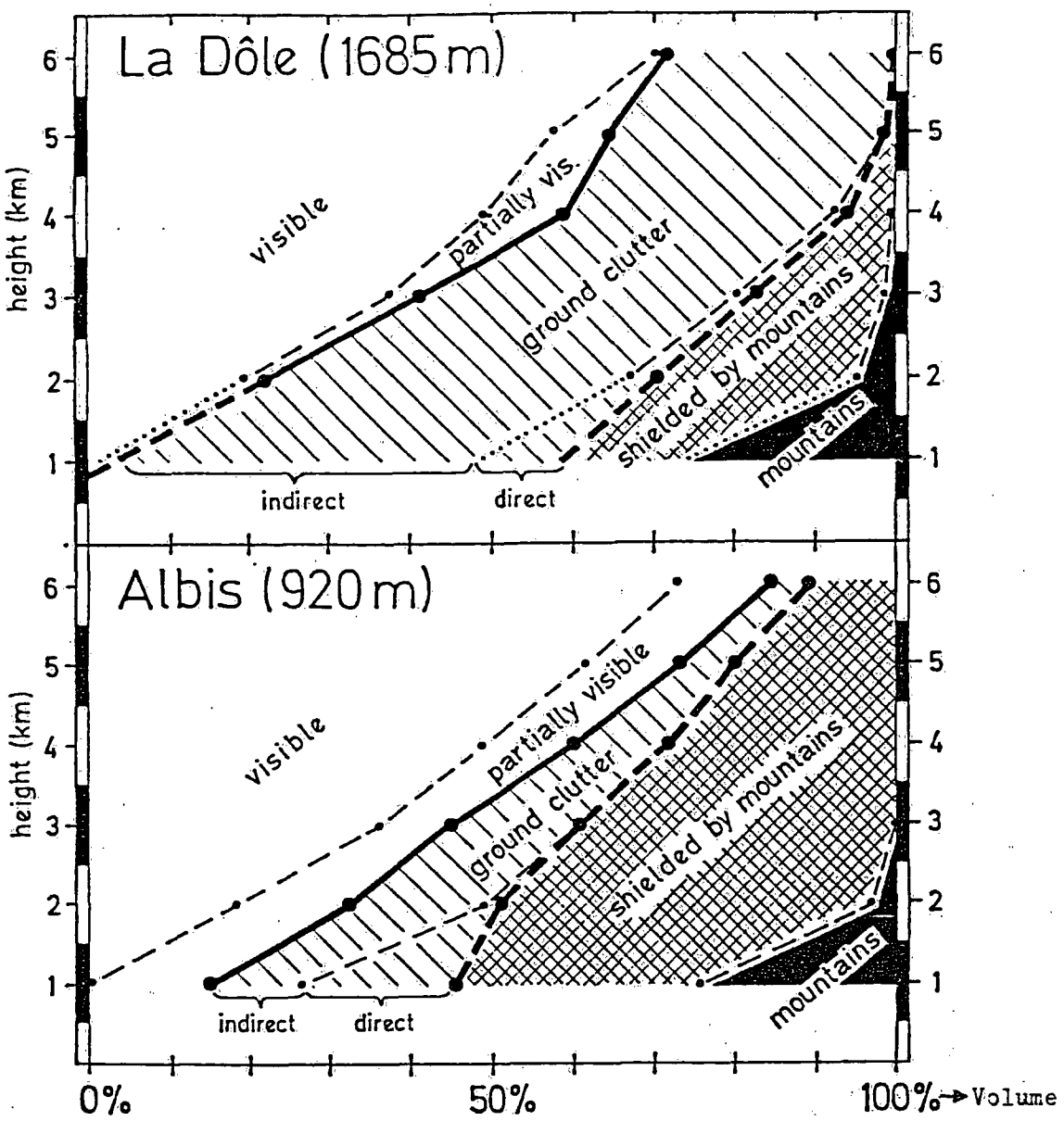


Fig. 3.1.2: Percentage of free volume for radar La Dôle (Albis) in Switzerland at an average distance of around 100 km as a function of height. Note that 100% in the figure contains only 19.6% (36.3%) of the area displayed in the radar picture (see Fig 4.6.1), as this analysis was made only for the Swiss territory where the raingauges are set up. We may distinguish the following regions, whereby the numbers indicate the values found for the layer between 2.5 and 3.5 km altitude:

1. Visible: All pixels with a dimension of 2x2x1 km3 are completely visible: 37.3% (36.0%).
2. Partially visible: A fraction of each of these pixels is shielded by mountains: 7.5% (8.8%).
3. Shielded by mountains: Pixels are behind mountains, invisible: 39% (17.4%).
4. Mountains: Pixels are completely in the ground: 0.8% (0.1%).
5. Direct ground clutter: Pixels contain clutter from the main lobe: 1.7% (0.8%).
6. Indirect ground clutter: Pixels contain clutter from the side lobes, i.e. the antenna is pointing to free space and inspite of that receives clutter echoes from the ground.

	Distance [km]	1	50	100	150	200
1 deg beam	Beam width 3dB [km]	0.02	0.87	1.75	2.62	3.49
	Beam width 10dB [km]	0.03	1.74	3.49	5.23	6.98
	Height [km]	0.01	0.59	1.50	2.72	4.25
	Radar/Gauge	99%	52%	19.3%	5.1%	0.9%

Table 3.1: 3 dB- and 10 dB-beam width, height of the beam axes above ground and resulting percentage of precipitation seen by the radar in flat country (amount of the rain gauge = 100%).

In this table an average reflectivity gradient in the vertical of -7.5 dB/km (reduction factor in rain rate of 3 per km) is assumed, which is reasonable in snow, on the average during the year. With less averaging, i.e. during shorter intervals of time, the fraction Radar/Gauge given in the table may vary with the weather situation around this value, e.g.:

1. A bright band may compensate or even overcompensate the reduction of sensitivity given above, leading to a radar-overestimate of up to a factor of 5, provided that the radar can resolve the bright band zone of the order of 300 m with a small enough beam width.

2. In convective situations higher reflectivities of short duration may also be found aloft.

Summing up we find at the average range, where operational weather radars are used today, that the error caused by clutter and shielding may be large and strongly variable, even in a flat country.

3.2 Errors Caused By Attenuation

Two kinds of attenuation may be identified, attenuation caused by atmospheric gases in the clear atmosphere and attenuation due to the precipitation itself. Attenuation caused by atmospheric gases is accurately known (1.5 dB for reflectivity or 25% for rain rate per 100 km at 5-cm wavelength). It is constant and may in many cases be corrected by including it into the range correction. Attenuation caused by rain may vary strongly according to the rain rates along the path, but in many applications plays a minor role compared to other errors provided a wavelength of 5 cm or longer is used. In European countries at the 200 km range, half of the true rain rate will be indicated at 5 cm wavelength in rare cases only. If the radar beam is travelling for some distance along the bright band, severe attenuation amounting to several times the value found in the rain below will be encountered (Joss et al, 1974). This situation may occur, when the bright band is at the altitude of the radar site, e.g. on a mountain top.

Many attempts were made to correct the attenuation during the data analysis by using the reflectivity measured along the path. However Hitschfeld and Bordan (1954) had already pointed out that the correction very easily becomes unstable caused by errors in the radar calibration, because of the variability of the relationship between reflectivity and attenuation, and caused by the echo fluctuation problem. The correction is therefore limited to a maximum of the order of 5 dB (Geotis 1975b).

Errors caused by a wet radome surface may be significant and will depend upon the rain rate, the wavelength and the surface conditions of the radome. For this type of error 5 dB (factor 2 for rain rate) of attenuation will be an upper

limit at 5-cm wavelength and will only rarely occur (Hudlow et al 1979). Knowing the rain rate at the radar site and having a good knowledge of the attenuation versus rain rate (Nakamura ?? RRL, Tokio), one may probably correct for a large part of this error.

Aydin et al. simulate with drop size data the attenuation of horizontally and vertically polarized waves in view of using 5.4 cm waves for ZDR-measurements and conclude that errors caused by the differential attenuation may be corrected and that this wavelength is therefore adequate for ZDR-measurements in most applications.

3.3 Errors Caused By Sampling

Errors when sampling the distribution of drop sizes: When deducing Z-R relationships it is important to pay attention to the fact that a small sample size (of 1 m3 or even 0.1 for certain applications) imposes a strong statistical fluctuation on the variables and laws between these variables. This fluctuation may remain undetected if these variables are deduced from one single instrument (e.g. raindrop sampling devices). The reason for that lack of realising the limits of our measurements comes from the high, artificial correlation between the variables (Figs. 3a and 3b of Chandrasekar and Bringi 1986a and 1986b), which is independent of sample size (Fig. 2 of Chandrasekar and Bringi 1986a). Simplified this means, that the same large drop of a small sample distribution contributes in a major way to the reflectivity as well as to the rainfall. However the statistical fluctuation shows up in its full, true amount, as soon as we are comparing results from different instruments together, such as radar and raindrop sampling devices. The only mean to reduce this noise is by increasing somehow the sample size. But doing that, we often find other problems, such as continuity in time or space of our variables, because the weather changes. To avoid misinterpretation, these questions have to be considered, if possible before doing the experiment!

An order of magnitude for the errors caused by sampling compared to the natural variation (the one we would like to investigate!) of a given parameter may be found in Joss and Gori 1978, p. 1058. E.g. the variation of the shape of the distribution (shape factor), measured by 4 independant instruments set up side by side to determine the error caused by sampling, is equal to within 3.5%. This is 3 times smaller than the 'real' changes from one minute to the next one, 5 times less when comparing distributions taken at a different moment within the storm (but at the same rain rate) and 10 times less than when taken at random within the same storm. In other words, distributions of this sample size (50 cm2 and 1 min exposure time, corresponding to a volume sample of 3 m^3 for big drops, which matter for the sampling error) are well defined for this type of investigation.

Sampling by radar: The rain rate can easily vary by a factor of 10 within a 10 min period or within 2 km distance, both being about the best resolution we can obtain with modern weather radars over an extended area. P.M. Austin (1987) finds that 'the spatial variability of rainfall is so pronounced that a single gauge often does not sample representatively over an area, even as small as 4km^2'. This variability in the precipitation field is an important source of the scatter of unaveraged measurements, and justifies a rather coarse intensity scale with a typical resolution of a factor of 3 in rain rate (7.5 dB in reflectivity). Obviousely all the calculations and the data analysis (e.g. the transition from one step of reflectivity to the next one) have to be far more precise than the width of the step.
This variability is especially relevant in conjunction with the large difference in size of the volumes sampled by radar and raingauge. While the raingauge measures continuously at a single point on the ground, the radar samples, e.g.

once every 10 min, a volume high up, which increases in size with distance. E.g. at 200 km a 1-degree beam is 4 km wide (Sec.3.1), leading to a variation of reflectivity across the beam of up to 40 dB, and resulting in considerable errors (Zawadski 1984). The result is a radar picture which, at increasing distance from the radar, is smeared out more and more in the vertical and horizontal directions. The 'raingauge picture' on the other hand has usually only a small number of point measurements in the region of interest. A comparison of instant values for a given location of the two data sets must contain therefore a considerable scatter between the two answers. Aniol et al (1980) investigated the small-scale variability of precipitation and found that, in order to obtain a significant sample for the raingauge or the disdrometer, at least one hour of data derived from three instruments was needed (see also Cain and Smith 1976). Zawadzki (1981) calculates the error caused by a non-homogenous reflectivity field. E.g. he finds that a reflectivity gradient of 10 dB across the 3-dB beam width increases the effective beam width by over 30%.

Not only the integration of a variable reflectivity field in space may lead to errors. To estimate precipitation, we have to integrate the rain rate in time, which also vary over orders of magnitude. If this is done with a scale other than the linear scale of rain rate, important corrections may be necessary. An example for such a correction is the one needed when averaging the logarithm of the reflectivities. The correction, only caused by fluctuations in the radar signal, is in this case 2.5 dB. This is constant in all weather situations. Other corrections may be even more important and depend on the distribution of the intensities of a given precipitation situation. Joss et al (1974) estimate in the appendix: 'Living in Log' the bias k and find the following formula, where sigma is the standard deviation of a Log-normal distribution and AVE(Z) is the average reflectivity:

$$k = \log(AVE(Z)) - AVE(\log(Z) = 1.15 * (sigma)^2 \qquad 3.1$$

E.g. for a standard deviation of 10 dB we obtain a bias of 11.5 dB! Wilson and Brandes (1979) in their Fig. 2 show the effect of the sampling interval on gauge/radar comparisons in practice. While the relative dispersion increases from 20 to 60% when the sampling interval changes from continous to a sample every 30 min, the bias of the factor gauge/radar changes from 1.2 to 1.5. The authors do not give any reason for this increase of underestimation of the radar with increasing sampling interval. The main reason is probably caused by the fact, that the gauge, while sampling continuously, misses nothing, even at longer sampling intervals of the radar. McAdie and Holitza (1986) investigate the influence of the sampling in space (150 to 1950 m in range and 1 or 2 degree in azimuth), and Huebner et al (1986) give results for the absolute percentage error of sampling intervals up to 40 min and of storm durations up to 190 min. Errors caused by sampling are also discussed in David et al (1986).

3.4 Choice Of The Wavelength

Using 10-cm wavelength or longer avoids errors caused by attenuation by precipitation in most situations. However at 10-cm, the relationship between precipitation and clutter is worse than at shorter wavelengths. The difference of this relationship between 5 and 10 cm wavelength is important and amounts to a factor of 16. In other words at 10 cm clutter echoes are 12 dB stronger in respect to precipitation than at 5 cm, assuming that the main contribution to the clutter comes from the sidelobes, which will usually be the case (Sec.3.1). Furthermore, and even worse, for the same antenna size the angular resolution of the radar beam would be reduced by a factor of 2 leading to large errors caused by the reduced spatial resolution at long ranges. 3-cm wavelength, on the other hand, would be better in respect to clutter discrimination and angular resolution, but is severely attenuated in heavy rain. By using a narrower beam,

obtainable with either a larger antenna or a shorter wavelength, the better spatial resolution will reduce ground clutter (echoes from ground targets). The optimum solution between these contradicting requirements regarding the wavelength depends upon the type of precipitaion to be investigated. Obviously heavy rain or hail require a longer wavelength and a larger antenna size (e.g. 10 cm wavelength and 8 m antenna), whereas for measuring weak rain or even snow 3 cm wavelength with a correspondingly smaller antenna of 2.4 m will be acceptable. The financial impact of the wavelength and the resulting antenna size is important, as cost increases roughly proportional to the weight of the antenna, that is with the third power of the wavelength.

3.5 Considerations When Choosing A Radar Site For Hydrological Applications

The question often arises, what may be done to reduce the errors caused by the vertical reflectivity profile discussed in Sec 2.4. Actually one solution is to choose the right compromise for the radar site. Smith (1972) discusses siting considerations in a flat country and whether the radar for quantitative work should be put on a tower or not. His answer is that it depends on the application. Among the questions discussed by Clift in the WMO report No.181, arguments are discussed as to whether a radar should be put on a high mountain with good view or whether a low altitude radar site is preferable. The answer, however, is left somewhat open. The experience with Swiss radars clearly gives preference to the first solution on the mountain top. This preference stems from modern data processing which will reduce many problems caused by clutter contamination found on a high radar site (e.g. using a dark target map as done in Switzerland or making use of the clutter suppression with Doppler radar). On the other hand nothing can be done to detect precipitation, which is blocked by using a low radar site.

3.6 Hardware Calibration Of Radar Systems

As discussed e.g. under the chairmanship of E. A. Mueller in the 'Weather Radar Calibration Workshop' in 1974 in Norman, Oklahoma, the hardware calibration includes the following: The calibration of transmitted power, antenna gain, beam width, antenna pointing error, pulse duration, receiver sensitivity, log receiver transfer function, correction for range and display equipment. Usually the manufacturer is in the best position to indicate an easy-to-use and accurate procedure for the calibration of his hardware. This type of calibration is certainly important and provides the basis of quantitative radar work. However, not knowing as precisely as one desires the absolute value of a certain quantity (e.g. receiver sensitivity), may be not as harmful as one might expect, provided that the system as a whole is stable. With modern radars the stability usually is no problem. Deviations from the normal relative calibration are probably smaller, and definitely easier to measure, than to determine errors connected with many methods to get absolute electrical hardware calibration (microwave values). If the system is stable, the meteorological calibration - or better adjustment - our ultimate aim, may be obtained directly against the desired meteorological quantity, e.g. rain amount measured by gauges on the ground (next section). This is more appropriate, because in this way the meteorological sources of error are also included in the adjustment, and these are dominant compared to instrumental errors in most cases for modern weather radar.

Using up-to-date solid-state electronics, it is possible to keep the total cumulative error of transmitted power, antenna parameters, noise figure, amplification in the receiver chain and A/D-conversion well within 2 dB or 36% error of rain rate (Geotis 1975a). David et al (1986) discuss the calibration of the radar Rodin close to Paris. The easiest way to reduce errors and maintain stability consists in using few and stable components, avoiding special devices,

such as ultra-low-noise and narrow-band receivers or devices for obtaining polarisation diversity. In fact over the last few years, using these guidelines, the standard error of the operational monthly overall calibration for the Swiss radars was kept below 0.5 dB. In this calibration everything is included between the output of the antenna (the directional coupler) and the display equipment of the user. Obviously this positive result reflects the stability, not the absolute accuracy of the equipment.

In conclusion we may say that careful calibration and development of new instrumentation for automated checking of the radar performance (as proposed e.g. by King 1981) is certainly desirable and important to reduce the time needed for maintenance. However our main effort should concentrate on reducing errors caused by meteorological features, which are the main limitation of the accuracy of modern operational weather radars (next section).

5.7 Meteorological Adjustment And Correction Of Radar Data

Rather than trying to assess all the individual radar parameters on an absolute basis (using microwave test equipment, spheres suspended from a balloon or corner reflectors) a probably easier way is to make sure that the radar hardware works within the specifications and is stable (as checked with microwave test equipment and discussed in the previous section) and to use the desired quantity itself, e.g. precipitation at the ground, for making the final adjustment of radar. For this purpose raingauges can be used, but before considering any adjustment with raingauges, the correction for the vertical reflectivity gradient should be applied by estimating the shielding caused by the known orography and by using the information about the vertical reflectivity profile estimated by the radar itself. A similar procedure has been proposed by Schmid and Waldvogel (1986) to estimate the kinetic energy of hail at the ground (Sec 5.8).

To compensate to a first approximation for the reduction of sensitivity at longer ranges an additional range dependant correction was introduced in 1981 in the radar equation used in Switzerland (Galli and Joss 1983). This very crude correction is currently still in operation and brings a definite improvement, but the method described in Sec.6.1, now being tested on an experimental basis, brings far better results.

Only after corrections for vertical reflectivity gradient and range have been applied, all available information about the Z-R relationship should be considered and raingauges be used to make the final adjustment. Here special caution and rules have to be observed otherwise one risks making things worse. Cain and Smith (1976) or Smith and Cain (1983 p.13) demonstrate this problem clearly and show, that to make things better, the standard error of the gauge (representativeness) has to be smaller than the bias of the radar.

Koistinen and Puhakka 1984 also find, that a real-time, 'instant' adjustment of the radar using telemetered raingauges is not as easy to accomplish as one might expect: e.g. the sampling problem of the raingauge in time and space has to be acknowledged by integrating the results over an hour or more, by using several raingauges for a given region of interest or use cumulative frequency distribution functions of precipitation amounts derived from radar and gauge values. To reduce the number of samples (raingauges, measurements in time) and to be able to correct in real time on an operational bases, Cain and Smith (1977) propose to use a sequential analysis strategy and apply it to rainfall computations (Smith and Cain 1978 and 1983). The sequential test discriminates against random variations (i.e. waits with a correction), but identifies systematic differences between gauge and rainfall estimates. Obviously to make this method work efficiently, we need to eliminate any known bias (Sec.4.6)

before we apply the test. This bias may be variable e.g. caused by to variable shielding as the storm moves and/or developes. The chance for the test to be significant will in this way be much better.

Krajewski and Ahnert (1986) give a brief, excellent introduction in multivariate analysis of raingauge and radar data, explaining how cokrieging works. Ahnert et al (1986) propose the application of a Kalman filter to the raingauge data to be used for estimating the radar rainfall field bias. From simulations they conclude this procedure to be significantly better than just comparing averaged values. Creutin et al (1987) use in their 'geostatistical approach' the so-called 'simplified cokrieging method' and conclude for 11 daily rainfall events, that inspite of severe limitations (ground clutter), the method appears to slightly improve the performance of the raw radar data and exceeds that of the classical uniform calibration method.
Little experience is available so far on an operational basis, and much work has still to be done. E.g. the question is open as to what extent the bias is a continuous function in space or whether it is discontinuous, which could be investigated by studying the fractal behaviour of radar echoes of different scale (e.g. Rys and Waldvogel 1986). Collier (1986b p. 233) finds that 'a simple substitution technique involving the best predictor gauge to the point for which the estimate is required, is likely to be as satisfactory as more complex methods'.

The radar data may be corrected with the "Aneich" factor, as described by Attmannspacher et al (1970, results are presented by Riedl et al, 1984) or with the "domain adjustment technique" proposed and tested extensively off-line by Collier et al (1983) using raingauges considering wind-dependent orographic effects and the development of the assessment factor with time. The improvement obtainable with a raingauge adjustment procedure is described by Riedl et al (1984) and by Collier (1986b).

In conclusion we may say that the adjustment of a weather radar will consist of four parts:

1. Make sure that the hardware is stable by calibration and maintenance (previous section).

2. Correcting for errors of the vertical reflectivity profile (Sec 6.1).

3. Taking into account all the information about the Z-R relationship (Sec.2.2, 6.3, 6.4, etc).

4. Adjusting with raingauges (this section).

Note, that the first three parts are based on known physical laws and only the last one uses a statistical approach. This will allow the statistical methods to work most efficiently.

3.8 State Of The Art

Well-defined catchment area (river basin): Small errors may be obtained at ranges, where the radar is able to see rain only, provided that well-placed raingauges are used for adjustment. E.g. in a hilly terrain, Harrold et al. (1974) found an error of 37% for hourly rainfall amounts at a point. Increasing the integration time to 6 hours or integrating over an area of 500 km2 lead to an error of only 13% and they even hoped for a further reduction in flat country. Boucher and Wieler (1985) find excellent agreement between ground truth and radar measured snowfall rate and accumulated snow depth for 6 Massachussetts snow storms. The area within which such a high accuracy is possible, is limited

by the orography, the resolution of the radar beam (antenna size - wavelength) and, in rain, the height of the melting layer. In addition, high standards for equipment, calibration and data-processing are required. In general, however, these types of measurments are only possible close to the radar (up to 50 km).

General case (ranges over 50 km), rain and snow: If measurements are to be made at longer ranges, where the vertical distance between the sample volume of the radar and the ground is considerable, or if part of the beam intersects the melting layer or snow, the spatial and temporal variability of the assessment factor will increase. Furthermore, a systematic underestimate of the uncorrected radar-measured rain amount is found. As mentioned, where detection below the melting layer or the cloud base is not possible (because of topography or other reasons) a reduction factor for the the precipitation amount measured by radar of around 3 per kilometer of height difference (Sec 2.4) is often found. The relevant height is the difference between the melting layer or the cloud base (whichever is lower) and the radar sample, e.g. if a radar samples at 5000 m (beam axis) and the 0-degree level is situated at 3000 m, the radar will measure roughly a 10-times smaller amount than the gauge at the ground. This fact also applies to measurements in snow and in this case is especially harmful, as the height of the radar sample above ground is important when calculating the correction factor. One may ask, why such a strong limitation of weather radar was not realised a long time ago. The main reason undoubtedly lies in the fact, that radar in a quantitative way was mainly used in research applications of the type described above within well defined catchment area, frequently limited to summer rains (example of an exception: Harold et al 1974).

Collier (1986a,b and c) investigate the accuracy of radar and the representativeness of raingauges in the range of radar coverage. In the first paper he concludes that using 5 telemetering raingauges to adjust the radar data, significantly improves the accuracy of measurement of surface rain within 75 km of the radar site on most occasions (1986a). All the data for a complete year are analysed for bias and random error, and divided into different groups such as frontal, shower, with or without bright band and convective. In the second paper he compares adjusted radar data with a network of independant raingauges and assesses the best method to obtain real-time rainfall data for use in flood forecasting systems. He concludes, that the most appropriate method depends on the rainfall type, and that in order to obtain more accurate estimates of rainfall with raingauges than with radar (within 75 km of the radar site) the gauge spacing would have to be at most 20 km. In the third paper, Collier and Knowles (1986c) apply the results of the previous papers to short term flood forecasting and conclude, that both gauges and radar may be seriously in error, that we have to find a way to cope with these errors and if this should prove difficult, only man-computer interactive techniques such as proposed by Browning (1979) in FRONTIERS may help (Sec.4.2).

The question arises how much Colliers results would be improved and whether the proposed procedures would be more efficient, if they were applied only after having corrected errors caused by limited visibility and variable vertical reflectivity profile. It may also be that this could significantly support the man in FRONTIERS to improve his interpretation or, even better, replace him in many situations as proposed in Conway (1987)? Today the FRONTIERs concept is already allowing for making such adjustments, but in an indirect manner by considering range correction profiles and making site-specific corrections for wind. Probably it would be more effective to use the difference of height known for each pixel and the actual vertical gradient of reflectivity to calculate the reduction for each pixel. Today, with existing equipment and software, it may not yet be easy to obtain automatically a representative vertical reflectivity profile, but even a crude estimate is by far better than considering it not at all (see also Koistinen, 1986)! In any case, when planning a new radar system, we should include the 3. dimension and the possibility to estimate vertical

reflectivity profiles for hydrological applications.

4 EXAMPLES OF APPLICATIONS

4.1 NEXRAD

Sarreals et al. (1986) give a short description and the scientific basis of NEXRAD, the Next Generation Weather Radar Program, now being developed and tested in the US. NEXRAD is functionally composed of a radar data acquisition system, a generation and distribution system and a principal user display processor. Products include velocity data, special purpose (alert message), severe weather, momentum analysis (time-height cross-sections of Doppler winds) and precipitation analysis (adjustable with a raingauge array of up to 50 gauges).

As Golden et al. (1986) state in their indroduction, NEXRAD systems will avoid labor-intensive procedures and increase staff efficiency for the modernized and restructured National Weather Services being planned for the 1990's. In respect to precipitation analysis, NEXRAD promises to provide 'frequent and more accurate regional and national maps of rainfall'. Hudlow et al (1983) and O'Bannon and Ahnert (1986) discuss the 'Precipitation Processing System' and Pratte and Keeler (1986) show, that NEXRAD radars will have a high sensitivity compared to todays operational radars. According to Hudlow et al (1984), about 160 of these systems for a price of the order of 3 Million Dollars each are planned to be built, of which 100 will be installed in the US in the eary 1990's. A livetime of 20 years and a total benefit for hydrologycal applications of 26 Billion Dollars is expected.

4.2 FRONTIERS In The UK

The concept of FRONTIERS (Forecasting Rain Optimised using New Techniques of Interactively Enhanced Radar and Satellite) was initially described by Browning (1979). This interactive display system, developed by the Meteorologycal Office, combines data from 7 radars and the geostationary European satellite METEOSAT to produce every half hour quality controlled rainfall and short period forecasts of precipitation. Collier and James (1986) describe, how weather radar information reaches the user in a timely and reliable fashion. Conway (1987) presents results obtained in operational use since 1986, describes the hardware and gives an outlook on future developments, where 'the most challenging and far-reaching one will be the application of knowledge-based system techniques to automate some of the operators interpretive and judgemental functions'.

4.3 COST 73 In Europe

The COST program (CO-operation in Science and Technology) is a program for West European States which see advantage in persuing joint research or development work. Collier et al (1987) discuss the activity in Western Europe aimed at establishing national radar networks in the context of the project COST-73 which has just started and will have a duration of 5 years. This project follows the recently completed project COST-72 which was concerned with the accuracy of radar to measure rain. Clift 1981 gives the outline, Newsome (1985) presents results of this project. Roesli et al (1987) describe the application of COST-73 to very short range forecasting such as for maritime weather, floods and avalanches, input to mesoscale models and wet deposition of pollution or radioactivity.

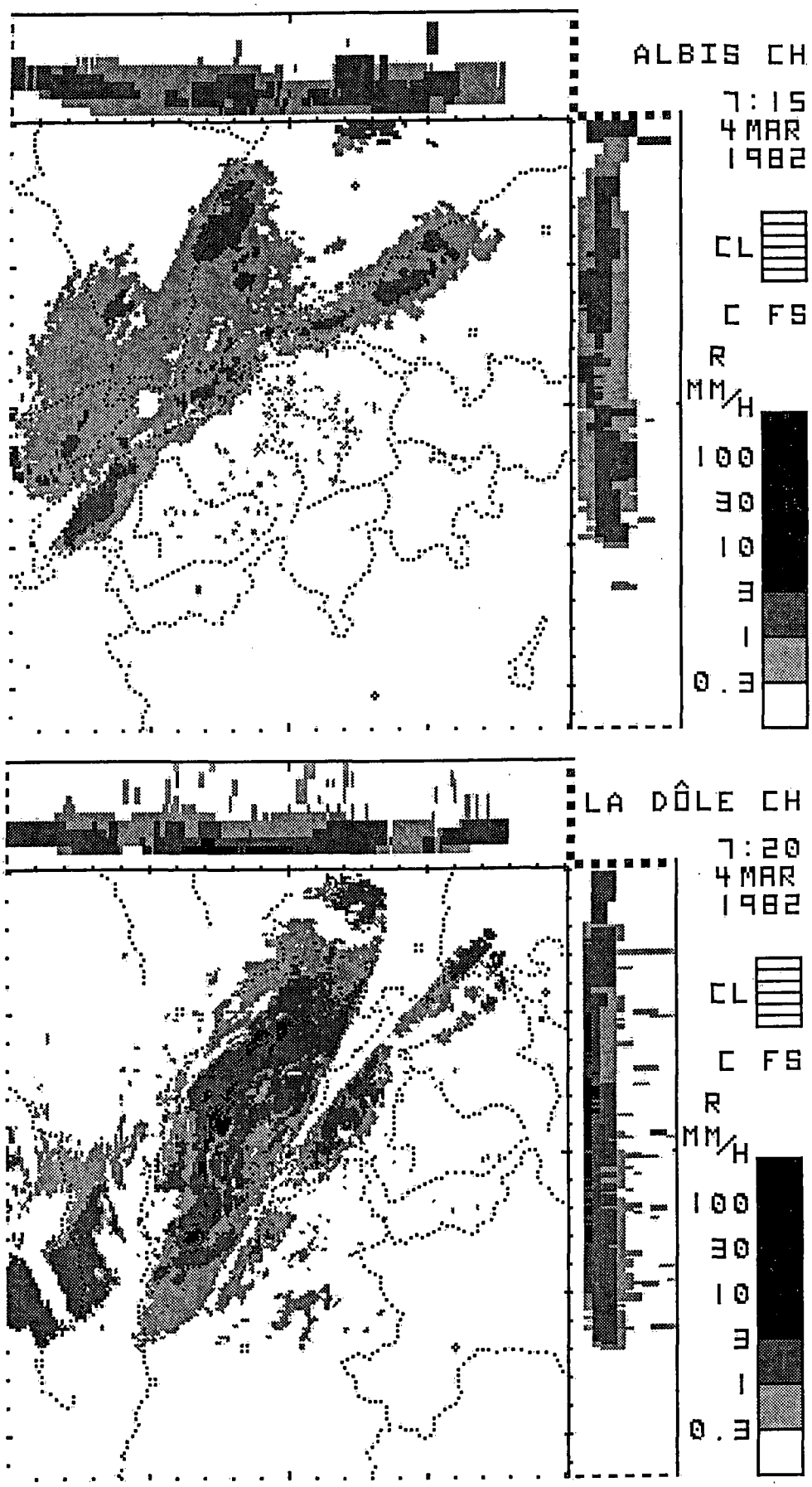


Fig. 4.5.1 (Text see over Fig. 4.5.2)

Fig. 4.5.1: The two pictures of the radars Albis (close to Zürich) and La Dôle (close to Geneva) indicate the weather situation of March 4 1982 0715 (top) and 0720 (bottom). The ground view (pixel size 2x2km2) shows a region of 400x430 km2, with the radar station in the centre. Rivers, political borders and some cities are also shown as an overlay. Front and side views present projections of maximum reflectivity between the ground and 12 km altitude. However precipitation in the figure reaches only an average height of the order of 7 km. The vertical resolution is 1 km, and for clarity, the vertical scale is expanded by a factor of six. The range of the rain rate is divided in seven equal steps on a logarithmic scale, the lowest step indicating intensities <0.3 mm/h and the highest one intensities >100 mm/h. But the case presented shows only intensities up to 10 mm/h. In the example the user has chosen to suppress ground echoes (CL = clutter) for the sake of clarity. The empty space to the north-east of La Dôle is caused by the radome close to an air traffic control radar. The coordinate system is relative to the radar station in the centre of the ground view.

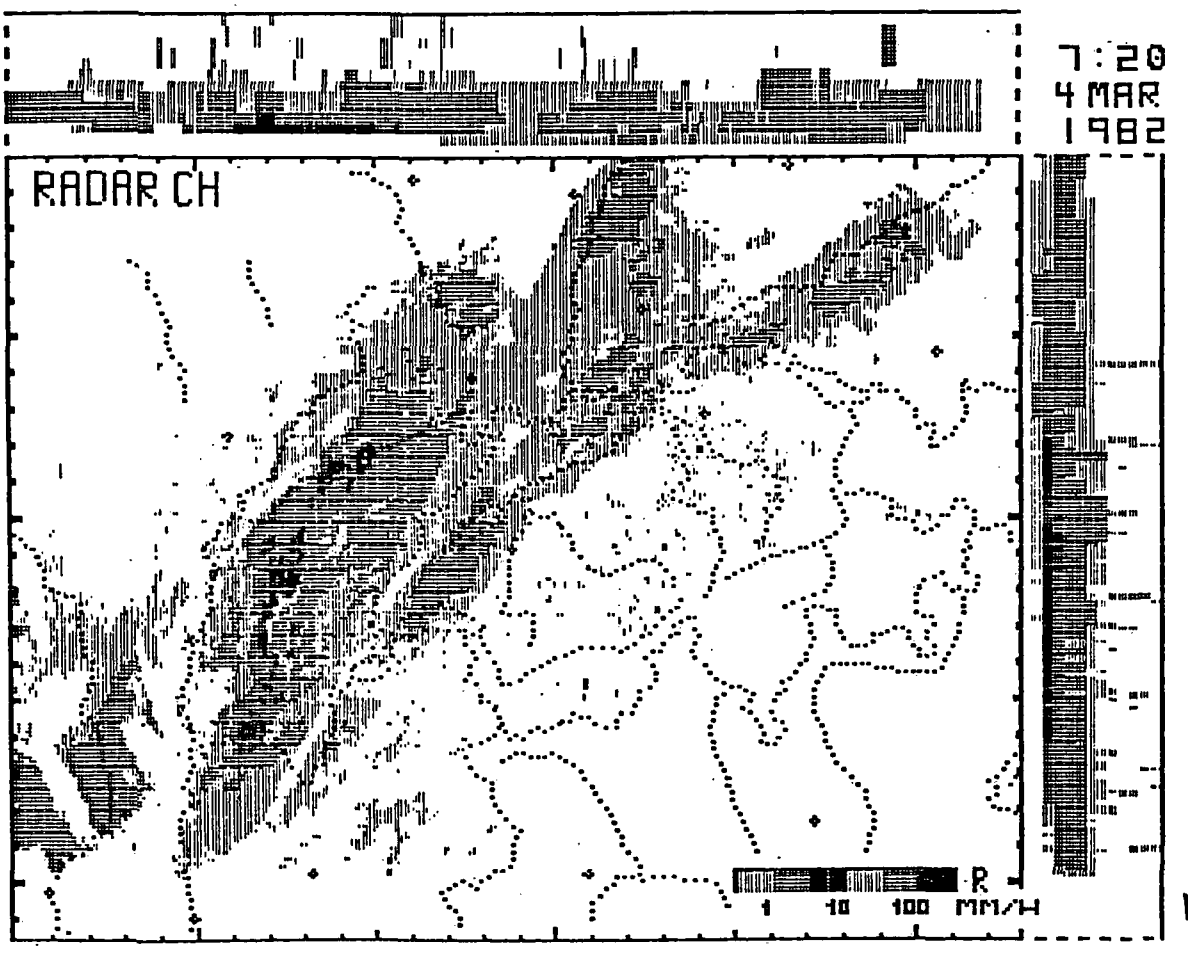
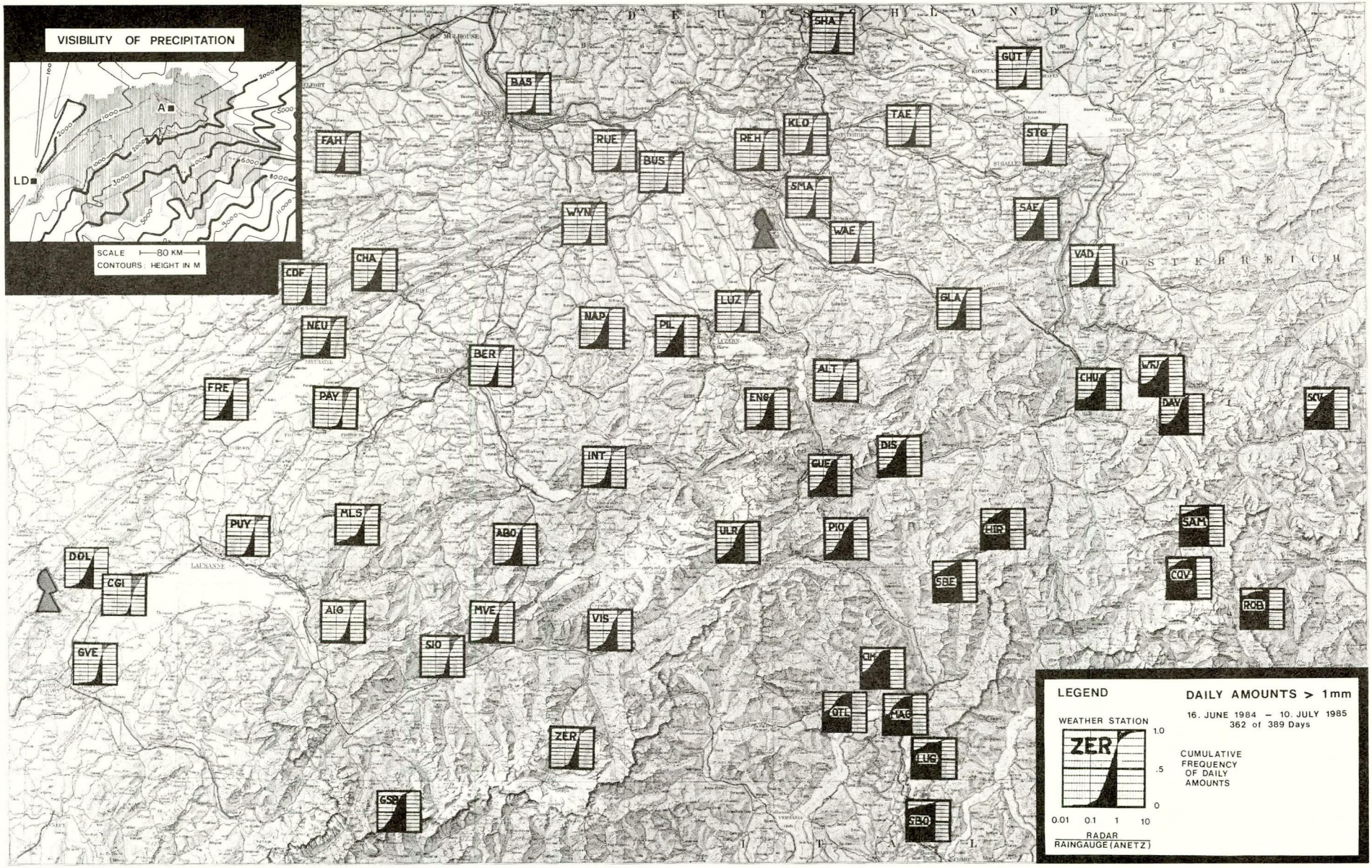


Fig. 4.5.2: In this radar composite of a region of 558x428x12 km3, the ground view contains all the radar information from both radars displayed in Fig. 4.6.2 The coordinate system corresponds to the official one used by the Federal Office of Topography. To generate the composite, the DISAT computer choses the "better" information from the two radars, i.e. the one without ground clutter or if both are free of clutter, the one with the stronger intensity, which usually originates from the radar seeing closer to the ground (Sec. 2.4 and 3.1). E.g. as a result the blind sector of radar La Dôle shown in Fig. 4.6.1 disappears, i.e. it is replaced by data from radar Albis.


VISIBILITY OF PRECIPITATION
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BER
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CHU
WYJ
DAV
FRE
PAY
ENG
SCU
DIS
INT
GUE
MLS
PUY
ABO
ULR
PIO
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CGI
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COV
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MVE
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ROB
GVE
SIO
ZER
LUG
GSB
SBO
LEGEND
WEATHER STATION
ZER
1.0
.5
0
0.01 0.1 1 10
RADAR
RAINGAUGE (ANETZ)
DAILY AMOUNTS > 1mm
16. JUNE 1984 – 10. JULY 1985
362 of 389 Days
CUMULATIVE FREQUENCY OF DAILY AMOUNTS

Fig. 4.6

Fig. 4.6: Overview on the operational measurement of precipitation with radar in Switzerland. The figure shows results of the quotient derived in dividing the precipitation amount measured with radar by the amount from the raingauge. The rain amount derived from radar was calculated from the echo visible above each raingauge location. In the figure cumulative frequency distributions of the quotients are depicted. Daily amounts of precipitation at 58 locations of the Swiss network of automatic weather stations (ANETZ) were calculated. The data base included 362 of 369 days between June 16 1984 and July 10 1985. At each geographical location of the raingauges in the figure, small graphs give the cumulative frequency for all cases with more than 1 mm of rain collected by the gauge.

We find good agreement between radar and gauge if the dark areas in the graphs are small. In other words, the area is a measure of the error, i.e. the deviation between the curve and the vertical line corresponding to the value of 1.0. In the case of Zermatt (ZER in the figure, note also the enlarged example in the lower righthand corner), the curve tells us that the radar indicates in 80% of the cases too little precipitation and in 20% too much. Note the logarithmic scale of the quotient on the abscissa. Again, in the case of Zermatt, we find in 10% of the cases, that the radar measured amounts of precipitation which are more than five times smaller than the corresponding gauge value.

The figure shows good agreement in the neighbourhood of the radar station La Dôle (close to Geneva) and Albis (close to Zürich). In general the agreement becomes worse when the precipitation over the gauge is less visible to the radar. To indicate a measure of the visibility, we find in the upper lefthand corner the minimum height to which precipitation must reach to be seen from at least one of the two radars. The visibility is calculated knowing the orography of Switzerland and assuming an equivalent radius of the earth of 8000 km. If this height becomes larger, as in the southeast corner of Switzerland, the underestimation of the radar also increases. The reason for this result is found in the fact that the echo intensity decreases with increasing height. On average, i.e. during all the storms for the whole year, we find a factor of three reduction per kilometer of height. As the decrease is less pronounced in convective situations in summer, the amount of rain in these cases can be measured with better accuracy than amounts of snow in winter.

The analysis were performed in the context of a research program at the Osservatorio Ticinese in Locarno of the Swiss Meteorological Institute in Zürich. The map is reproduced with the permission of the Federal Office of Topography from the 31.10.1985.

4.4 The French ARAMIS/METEOTEL

The concept of ARAMIS, a project to assemble, distribute every 15 min and display on the lowcost METEOTEL terminal information of 11 weather radars together with information of METEOSAT, is found in Gilet (1987). David et al (1986) demonstrate the usefullness of radar to measure rain, and discuss sampling problems, calibration and simulation of a raingauge network for the radar Rodin near Paris.

4.5 The Swiss Composite

Since 1979, the information of the two weather radars of the Swiss Meteorological Institute (SMI) is distributed in digital form over leased telephone lines. The most important of a total of some 15 users are the forecasting centres of Zürich, Geneva airport, Kloten airport and Locarno-Monti of the SMI. The information of two radars (Fig. 4.5.1) is combined into a single composite picture covering an area of 562x434x12km3 (see Fig. 4.5.2). This picture is transmitted 24 h a day every 10 minutes via phone line to all users (Cavalli 1984). Both radars are unmanned and identical in design and operation. There exists no dialogue between the radar sites and the users, and only one type of picture is available. This picture has to give a survey of all the relevant features of the current precipitation.

The advantage of a picture with the three projections of the maximum intensities is, that it retains location, height, extent and reflectivities of the heaviest weather as non-averaged values. In fact we find that for a routine use in an extended mountainous area of an orographically difficult country, such as Switzerland, the use of maximum projections is the only practical way of displaying radar data. Applications may be found e.g. in Roesli (1984) and a descripition of the used compositing algorithm in Galli (1984). Within minor restrictions imposed by the projections of maximum reflectivitly, the vertical reflectivity profile, needed for improving estimates of rain rate at longer ranges, may be extracted from the picture.

4.6 Comparison Of Radar And Precipitation Gauge Data

The problems arising from the vertical reflectivity profile, ground clutter and shielding, described in Sec. 2.4 and 3.1 shall be illustrated now by investigating the agreement radar/raingauge in an operational system: 2 combined 5 cm radars and the raingauge network of the Swiss Meteorological Institute. The 'advantage' of the Swiss configuration is the (radarwise) very difficult topography, which demonstrates shielding problems so drastically, that they cannot be overlooked:

The data: It will be shown, what quantitative information may be extracted from the data distributed to many users as described above. 362 out of 389 days between June 16 1984 and July 10 1985 were analysed to find the accuracy of radar on an operational base. This included 100'000 volume scans (from the two radars), each of which was extracted from 1000 Million bits of raw radar information. From this data, daily amounts of rain were calculated over 58 raingauge locations and compared with the amount measured by the raingauges below the corresponding radar volume. An overview on the agreement between radar and gauge is found in Fig. 4.6.

Results: Some results about the percentage of rain seen by the radars as compared to that measured by the raingauges are given in the tables below. The results are given for all days with more than 1 mm of rain, days from the summer or from the winter only, and days with weak rain or with heavy rain. Results are

presented for the single radars La Dôle and Albis and for the composite. The results clearly show that the composite information, which is transmitted to the users, contains better information than either of the two radars. La Dôle measures considerably less precipitation than Albis caused by its larger average distance of 134 km (compared to 101 km) between the radar and the gauges. By normalizing the results of La Dôle to the same average distance as Albis, La Dôle is better by having a higher radar site (1685 m instead of 920 m for Albis), causing it to see further and enabling it to look down into the valleys.

	All days rain >1 mm	Summer rain >1 mm	Winter rain >1 mm	Days with 1<rain<10mm	Days with rain >10 mm
La Dôle	16%	16%	7%	16%	10%
Albis	25%	35%	10%	22%	20%
composite	40%	50%	29%	45%	25%

Table 4.6.1: Percentage of precipitation amount seen by the radars as compared to the raingauges: 100% would be seen by the ideal radar. The Swiss radars were ajusted with raingauges close to the radar to see 100% (as may be verified in Fig 4.6), but inspite of that, the radar sees much less over the average gauge: For half of days and for half of the stations, the radar sees only more than the indicated percentage. E.g. Albis sees in winter only one tenth of the rain of the gauges.

As the analysis are made for each station separately, the number of days considered can be different for each gauge. At first glance it is surprising that the radar sees a smaller percentage for higher amounts, a result also found by Walton and Johnson (1986) when analysing CP-2 data for the precipitation project procedure of NEXRAD. Four reasons are responsible for that fact:

1. Echoes responsible for larger amounts do not necessarily reach to a higher altitude, which is the main condition to be detected and to obtain a high percentage.

2. Larger amounts are usually produced by weaker, or more widespread rain of long duration.

3. The gauge was chosen for selecting the group (weak or strong). This produces a bias (lower percentages at higher amounts).

4. The distribution of rain amounts is asymmetric (higher density of lower rain amounts).

We find a significant underestimation of precipitation measured by the radar. Detailed analysis shows that this is a result of earth curvature or blocking of the lower parts of precipitation by topography . As the percentage seen by the radar not only depends on the degree of shielding (which is constant for a given location), but also on the decrease of reflectivity with height in a given weather situation, this percentage is variable for a given location. This variability was investigated and the results presented in Table 4.6.2. The variability is large and reflects the variation of the vertical reflectivity profile. The next step is to investigate, to what extent it is possible to estimate this profile from the radar display and correct the values in real time by knowing the amount of shielding for each point in the radar display.

	All days rain >1 mm	Summer rain >1 mm	Winter rain >1 mm	Days with 1<rain<10mm	Days with rain >10 mm
La Dôle	3-40%	4-63%	2-23%	3-48%	2-25%
Albis	4-74%	10-81%	0-32%	4-100%	6-40%
composite	11-91%	20-100%	8-68%	14-112%	11-51%

Table 4.6.2: Range of variation of the fraction seen by radar. The two values in each field give the range of fraction during 68% of the days of a given population. E.g. as indicated in the first column of the table, the radar Albis measures 4 to 74% of the rain in the sampling volumes above half of the raingauges. In other words, on 16% of the days it finds less than 4% of the precipitation and on 16% of the days it finds more than 74% of the precipitation measured by the gauge (16% + 16% + 68% = 100%). The fraction (radar/gauge) is indicated in %, e.g. 112% means that the radar overestimated the gauge amount by more than 12% in 16% of the cases over the better agreeing half of the total number of raingauges. Even stronger under- or overestimation of the precipitation measured with radar occured over the other half of the gauges.

Conclusions:

1. Good results (reproductivity) are obtained at short ranges, where the distance between the illuminated volume and the raingauge is less than a few hundred meters.

2. On average, throughout the year, a reduced sensitivity by a factor of 3 per km of height is found caused by shielding. In convective rain below the melting level the reduction may be somewhat smaller. Summer rains, in which the decrease of reflectivity only starts at higher altitudes and which usually have higher echo tops, are measured more accurately than winter precipitation.

3. The average underestimate (bias) and variability of the sensitivity of radar increases dramatically at longer ranges because of the width of the radar beam and the vertical distance between sampled volume of radar and raingauge.

4. At longer ranges (50 km or even less in Switzerland, depending on the topography, the type of storm, the season etc) shielding is dominant compared to other sources of error, including Z-R.

5. One may call the observed deviations a problem of Z-R, but we would rather not refere to it in this way because deviations are frequently caused by not seeing precipitation immediately above the raingauge; Z and R simply do not belong to the same volume of the atmosphere.

6. Observed deviations are not caused by problems with the radar calibration of the hardware. The stability of modern hardware and test equipment is such, that instrumental errors can be kept negligible compared to other errors.

7. The radar site has to be selected carefully. A higher radar site may be preferrable inspite of more clutter, because there are means to suppress clutter but none to bring back precipitation hidden behind an obstacle. Of course this must be related to the question of scale of individual storms (vertical profile and horizontal extent of the precipitation) and area to be covered by the radar.
Both radars in the example above show the same general behaviour,

however the higher sited radar is somewhat poorer than the lower one (Albis) on an absolute basis, but better when compensating for the longer distances to the gauges.

8. The results presented above demonstrate the general advantage of overlapping radar coverage. Precipitation amounts, determined from the composite of two radars are considerably more accurate than from the individual radars. This is true for the bias as well as for the variability (tables 4.6.1 and 4.6.2).

9. For quantitative radar work we must have a rather dense network of radars. Therefore, an exchange of radar data between bordering states and countries will be most useful, and we need projects like NEXRAD in the US or COST 73 in Europe, coordinating the exchange of radar data between parts of the same country and between different countries.

5 TECHNIQUES

5.1 Area Time Integration

The measurement of precipitation by radar over a large area and its problems have been discussed above. One of the critical points is the shielding of echoes, other ones are the many factors which complicate the quantitative radar measurement and the transformation of radar reflectivity into rainfall rate. It is understandable therefore, that techniques to overcome some of these problems were investigated. Byers (1948) was one of the first to published results about the relationship between the amount of rain falling from a shower and its size and duration. This idea to use just a reflectivity threshold and parameters such as area and time instead of detailed reflectivities does not only simplify many problems, but it also opens the possibility to take satellite data to supplement incomplete radar measurements.

Doneaud et al (1984) proposed to correlate the area-time integral with rainfall amounts. The correlation between the two parameters in the cases analysed was such, that the technique of using area-time integrals promised to be comparable to the classical way needing Z-R relations. This concept has been developed to interprete satellite data by computing area-time integrals and successfully tried in a further paper by Doneaud et al (1986 and 1987). Area and time parameters of radar echoes have also been investigated for the detection and measurement of hail. Geotis (1963) found a critical time duration of a given reflectivity threshold, which clearly indicated hail on the ground. Then area-time integrals have been shown to be useful in deriving the kinetic energy of hailfalls (Waldvogel and Schmid, 1982).

5.2 Vertical Integrated Liquid Water Content

Geotis (1971) calculates instantaneous liquid water contents of several storms. Total rainfall rate, accumulated liquid water dimensions and duration of the storms are also given.

5.3 Attenuation

There are 3 main reasons for interest in measurements of attenuation (an extensive discussion is found in Atlas et al (1984)):

1. Estimation of path attenuation for communication links and for knowing and correcting errors when making reflectivity measurements (Sec.3.2). In this respect we know fairly well how much attenuation is to be expected in a given situation and correction is limited to a maximum error of 5 dB.

2. Obtain information about Z-R (Kozu et al (1986) or Meneghini et al (1986)): If this is done with a range profiling algorithm as discussed in Sec.5.4 of Atlas et al (1984), the question is open as to what improvement this technique will bring, considering that it can only be used for a selected linear path whereas in hydrology we are interested in an extended area.
   If on the other hand it is done using dual wavelength methods, it needs complicated, difficult (dynamic range, need for identical beams) and expensive equipment. This refinement will be acceptable and effective for operational hydrological work only (if at all) after the correction for the vertical profile is taken care of.

3. Estimate rain rate directly: Here the early deviation from the Rayleigh approximation, the A-R relationship lets us anticipate errors of the same order as when using Z-R relationships. Furthermore it needs dual wavelength methods and therefore the same comment as in 2. applies.

In conclusion operational attenuation measurements for hydrological applications are only usefull (if at all) after other corrections are already made.

5.4 Combination Of Data From Radar And Satellite

Collier (1986a) concludes, that satellite and radar techniques for measuring rainfall for hydrological applications are complementary and that radar is more apropriate for small basins (of the order of 10^4 km^2, a number which may be increased, if correction for the reduced visibility at longer ranges proves possible) while satellites are better for larger basins.

Bellon and Austin G.L. (1986) give empirical relationships for deriving areas with rainfall of prescribed rates. They find at 2 mm/h a Critical Success Index of 50%, a Probability of Detection of 70% and a False Alarme Rate of 35% (as defined by Donaldson et al, 1975) and conclude, that their objective technique is better than gauge interpolated estimates in locations, where the nearest gauge is farther than 40 km. Osano et al (1986) investigate the collaboration between radar (as ground truth) and GMS satellite data and find much better correlation for VIS- than for IR-data. They propose to investigate what can be done at night, when no VIS-data is available and to test this new technique all year round.

In conclusion we may say, that the reasonable approach will consist of adjusting radar with gauges as described in Sec.3.8, and using radar in turn to adjust satellite data (here ATI-analysis may be an interesting approach to follow, Sec.5.1). Whether this is best done with human interaction as used successfully in FRONTIERS (Conway 1987) or as proposed for the gauge/radar system by Austin P.M. (1987) or whether automatic ways of data analysis as used in RAINSAT (King 1987) and proposed by Bellon and Austin G.L. (1986) remains to be shown. The choice for a given application will probabely strongly depend on the availability of qualified personnel.

5.5 Flood And Avalanche Forecasting

Comparing radar data with river flow brings in a new variable. In other words, it liberates our radar-verification-task from the problem of point measurement and representativity of single gauges but adds a new problem to the complexity of the quantitative radar measurement: The one of fluxes, storage and delays in a river bassin.

As mentioned by Collier (1985), flood forecasting may lead to improved water management including flood and drought prediction. He reviews requirements for hydrology forecasting, groundbased radar techniques, the future potential of remote sensing and the need for a total system approach in the way proposed by Browning (1979) and being discussed and developed with different degrees of complexity in various countries. He discusses the use and advantage of models with different degree of complexity and defines various hydrological parameters. Gorrie and Kouwen (1977) used an existing low density network in Canada to ajust radar data, discuss the achievments obtainable with simple corrections for clutter and screening, and conclude that despite large percentage differences in radar-gauge validation comparisons, hydrological predictions were improved slightly in widespread rain and significantly in thunderstorm situations. Collier and Cluckie (1985) and Cluckie and Owens (1987) discuss the effect of the sampling interval and find that little information content is lost, when hourly rainfall accumulations are used (instead of an update of the model every 15 min) and that 'greater degrees of spatial and temporal variation can be tolerated in practical forecasting applications, than would first seem reasonable'. They expect that 'expertise gained in application will further improve the calibration procedures and that these improvements will gradually be realised at decision making levels, where models are put to practical use'. Cluckie et al. (1987) investigate flood producing storms and real-time hydrological forecasting models, the use of which 'has now been clearly established' and that 'future efforts are now being directed towards the further improvement of the operational use of such data'.

Kappenberger and Joss (1986) find in an exploratory analysis of four storms leading to a catastrophic avalanche situation, after correcting by hand for the vertical reflectivity profile, reasonable agreement between radar estimated melted snow and raingauge measured melted snow was found. They conclude that radar (together with automatic weather stations and manual observations) give valuable information about avalanche activity.

5.6 Urban Hydrology

When applying radar to predict the flow of water in the sewers of a town, similar variables and equations are found, but the analysis has to be done on a much finer time scale than when forecasting the flow of a river in a large basin. Roberts (1987) presents results for the Manchester area. Inspite of various difficulties he concludes tentatively, that 'the potential of radar in urban drainage models is such to warrant additional research'.

5.7 Short Term Forecasting

Probably the most attractive point of weather radar is the overview on the actual weather situation (Nowcasting) and the possibility to make short term forecasts. E.g. NEXRAD plans to produce short-term forecast of precipitation accumulations, updated at a scan rate interval for up to 1 hour into the future (Walton and Johnson, 1986). Austin G.L. et al. (1986) describe a sophisticated interactive processing system (Rapid II) which can be attached to a conventional radar to produce among other products short term forecast of accumulations, both

at selected points and over the field of view. The authors conclude that this low cost addition significantly enhances the cost effectiveness of conventional radar and allows to realize the potential of radar, recognised already 30 years ago.

5.8 Hail Detection And Measurement

The detection and measurement of hail by radar has been of interest since the beginnings of radar meteorology. Especially forecasters of severe weather and scientists working in hail prevention operations had a fundamental need for such a technique. And indeed, one of the first criteria used in the positive identification of dangerous hail clouds early in the life time of convective cells was developed by Soviet scientists working in hail prevention. The criterion relies on the use of the geometrical properties of a cloud which were originally measured using optical devices rather than radar.
A very simple criterion, using a 3 cm single wavelength radar only, could be derived on the basis of the above mentioned considerations. It can be expressed as follows:

$$H45 > HO + 1.4 \text{ km} \quad 5.8.1$$

It says that the height of the 45 dB(Z) contour must exceed the height of zero degree by more than 1.4 km. The criterion turned out to be very useful as it detects all hail cells (no misses) early in their life; however, about 30% of the cells identified as dangerous never produced hail on the ground. The test of this criterion has been done by comparing it with the measurements of a very dense hailpad network (Waldvogel et al 1979). The criterion is similar to the original NHRE criterion used in the declaration of a hail day in northeast Colorado, Foote and Knight, (1979), and to one used in a hail prevention operation in South Africa (Mather et al 1976). This result is unexpected in view of the different hail climatologies of these areas but can be explained easily from the cloud physics (Waldvogel et al 1979) which is supported with in situ airplane measurements. The same results found at different places and with different methods give further confidence in the general validity of the hail detection criterion.

So far we discussed the simple (yes/no) answer for a cell in respect of hail on the ground (hail detection) which can be gained with a simple radar criterion. However, much more complicated questions are of interest: Such as where, when, how large and what type of hail is encountered (hail measurement). For these questions more sophisticated techniques have been proposed and developed, such as multiwavelength radars (Atlas and Ludlam, 1961), radar using polarization ratios (Barge, 1972, Seliga and Bringi, 1976, Srivastava and Jameson, 1977, Bringi et al, 1986a,b). Some of these systems operated successfully and gave very interesting insights into the formation and internal structure of hail cells. The problem with all these methods, however, is that there are only few comparisons between radar data and ground truth. This lack of confirmation is even worse for radar measurements several kilometers above the ground. An attempt to overcome some of these problems is discussed by Aydin et al. (1986a).

With the measurement of hail by radar one would like to obtain as accurate a measurement as possible of the damage or the amount of hail on the ground. A first qualitative approach to this problem was published by Geotis (1963), whereas Waldvogel et al. (1978a, 1978b) presented a solution for the quantitative measurement of hailfall with a 10 cm radar. The procedure of this single wavelength method needs 3 steps: 1.) The Z-E relationship between the flux of the kinetic energy of the hailstones (E) and the radar reflectivity (Z), 2.) the scattering behaviour of the hailstones and 3.) the separation of radar echoes caused by rain from those due to hail. A straightforward solution for the relationship between E and Z is obtained by measuring the hailstone size

distributions. The advantage of this method is that E and Z are derived from the same sample and this eliminates problems caused by differences in sampling sizes or locations which are encountered in the case of a comparison between radar and hailpad data. Hailstone spectra have been measured at the ground in the centre of severe hailstorms with vehicles equipped with hailstone and raindrop spectrometers (Waldvogel et al 1978a). It leads to the following relation:

$$E = 5\ (10^{-6})(Z^{0.84})\ 5.8.2$$

where E is given in Joules/m^2s and Z in mm^6/m3. It is based on the assumption that the hailstones are spheres and Rayleigh scatters. This is a very crude simplification and does not consider the different aspects of hailstones such as the complicated shape, problems with water film on the surface, the ice/water structure and so on. These subjects have been studied in detail, for instance Srivastava and Jameson (1977). The third point mentioned above is the separation between rain and hail echoes. This is an impossible task with single wavelength radar. However, a simple solution has been proposed by Waldvogel et al. (1978b). It is the so called "cutting method", which neglects radar reflectivities equal or less than 60 dB(Z) because these are assumed to be caused by "rain only". Reflectivities greater than 60 dB(Z) are assumed to be caused by "hail only". This is rather crude, nevertheless it is hoped, that effects caused by this simplification are averaged out when the time or area integrals of hailfalls are considered.

An example for the agreement between hailpad and radar data, when using the above procedure is given in Fig. 5.8. It shows on the left the hailpad sites, their identifications, the kinetic energy value in J/m2, the areas represented by the hailpads and the isolines of the kinetic energy for 10, 30, 100 and 300 J/m2. On the right isolines of the kinetic energy for 10, 30, 100 and 300 J/m2 derived from the radar data are depicted. The resolution of the radar measuring points is 1/3 km compared to about 2 km for the hailpads. Therefore it is clear that the fine structure of the hailfall appears in much greater detail in this plot and shows marked differences from the hailpad data. The two time and area integrated kinetic energy values, however, agree well in this example: The value from the hailpads is 11.2 Giga Joules and from the radar it is 9.0 Giga Joules. Similar results have been found for other large hailstorms (Waldvogel et al 1978b) and also for medium and small hailstorms (Waldvogel and Schmid, 1983). The question now is: Did we solve the measurement of hail by radar? Before the enthusiasm about these possibilities becomes too large, however, the discussion about the generalization of well defined experiments given in Sec 1.2 should be remembered.

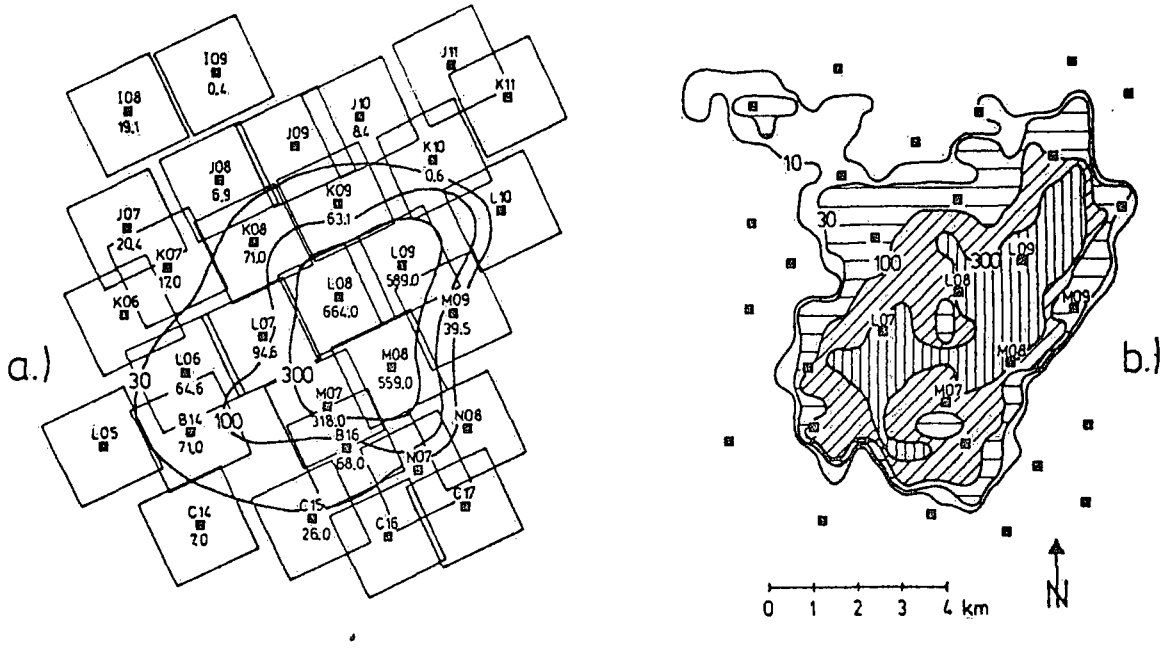

Fig. 5.8: The hailfall of June 1, 1978: The hailpad data are given in (a), showing the hailpad sites, energy values (J/m2) and areas represented by the hailpads. The radar derived isolines of E(Z) are plotted in (b) also J/m2.

Numerous possibilities to use more sophisticated techniques than single wavelength only, exist for the detection of hail as well as for its measurement, see also Srivastava and Jameson (1977), Aydin et al (1984), Method et al (1984), Al-Jummily et al (1986), Aydin et al (1986a) and Balaji et al (1986). A very promising technique is the dual wevelength method, proposed in 1961 already by Atlas and Ludlam. The dual wavelength technique has been developed and realized in context with the large hail suppression experiment (NHRE) (Foote and Knight, 1979). However, interesting enough, these measurements have not been used for the final evaluation of this experiment. There is only one paper comparing for several hailstorms dual wavelength echoes with ground truth measurements of hailpads (Eccles, 1979). The results and possibilities are encouraging, however, this technically ambitious method can at the present time still not be regarded as a routine technique. The same is true for other sophisticated methods as discussed by Aydin et al. (1986a). One reason for this situation might be, that the large amount of effort needed to develop the hard- and software for such systems does not allow to invest the necessary, further amount for the installation and maintenance of a dense and reliable groundbased network as ground truth.

6 OUTLOOK: METHODS TO IMPROVE THE ACCURACY OF RADAR DATA

6.1 Vertical Profile And Volume Scan

As Zawadski et al. (1986) state in their conclusions, the transformation of radar measurements into precipitation at the ground should be adjusted to every operational situation by considering the height of the radar measurement, the range of the radar measurement and the time and space resolution. If for hydrological applications we are not able to take radar samples directly over the ground, we must correct for that fact. To do that, we need to determine for each pixel the height of the ground, the height of the lowest visible volume (i.e. free of clutter and shielding) and a representative vertical reflectivity profile (Sec.2.4). To obtain this profile, some averaging in space has to be

done. Using this profile involves doing an extrapolation of a measurement aloft to the ground. Koistinen (1986) proposes to average the profile over a whole day in an area where the radar sees well. As a first approximation this is fine, but some more resolution (at least in time) may be usefull, as the weather situation may evolve during the day. Furthermore the correction has to be done conservatively, e.g. by not correcting the full amount calculated from the difference of height and the vertical gradient of reflectivity. In cases of poor visibility (strong clutter or shielding) we may even make no correction at all and use the calculated correction factor as a measure of uncertainity, i.e. a warning or limit of error when using the uncorrected results. Preventing illusions in cases for which the errors are large may already be an advantage!

Estimating the vertical profile needs a full volume scan. Having accumulated this information, we may, depending on the application, calculate other products such as a 3-D display using projections of maximum reflectivity. Besides complementing the knowledge of the meteorological situation, this display will ease the detection and tracking of significant weather for general aviation and gale warning. It allows reconstruction of the shape and position of the severe weather echoes in three dimensions which for many applications is most valuable. Furthermore, even when lower parts of the storm are shadowed by mountain barriers, this method always displays at least the elevated echo tops. Especially in a mountainous region these are remarkable attributes as compared to conventional displays such as PPI, RHI or CAPPI (Plan Position Indicator, Range Height Indicator or Constant Altitude Plan Position Indicator). Using these conventional displays the observer is tempted to follow a specific cell, not realising that in another location above or next to it, a much stronger cell has started to develop. To prevent this situation, data processing with conventional displays would have to be continuousely adapted to the changing weather, or crucial events would be overlooked.

6.2 Doppler Radar

For precipitation measurement with radar the main advantage of Doppler techniques lies probably in solving, in the spectral domain, some of the problems caused by clutter and anomalous propagation (Passarelli et al. 1981). Little experience with the necessary algorithms is yet available for operational applications (Sec.3.1), but we will soon know more about this subject, as operational radars in Sweeden (Persson and Lundgren 1986) and NEXRAD in the USA (Golden et al 1986) will have such means.

Hauser and Amayenc (1984) and others report about vertical air motion and measurements of drop size distribution, investigating the variations of NO and Lamda. Again, future work will have to show, how this valuable research can be applied to operational hydrological applications.

6.3 Polarisation Diversity

Using dual-polarisation techniques to estimate the Z-R relationship in real-time by radar seemed initially quite promising, inspite of the large added complexity with respect to instrumentation and data analysis. Hall et al (1984b) give the state of the art and discuss open questions after the URSI Commission workshop. However, reviewing the literature shows that the polarisation diversity techniques are still in the research stage (e.g. Bringi et al, 1984, Metcalf, 1984, Sachidananda and Zrnic, 1986, Stapor and Pratt, 1984), this inspite of the fact, that e.g. Lipschutz et al (1986) describe an 'operational ZDR-based precipitation type/intensity product'. The effect of the electric field on the shape of raindrops is discussed by Zrnic et al (1984), the equilibrium shape of raindrops by Beard and Chuang (1986), the shape of hailstones by Wang et al

(1987), the oscillations of raindrops by Beard (1984) and its influence on ZDR by Seliga et al (1984). Hall et al (1984a) give 6 rules for identyfying various hydrometeor types, ground targets and chaff. They conclude, that the use of ZDR in interpreting development of precipitation cells holds great promise. However after reading Hendry and Antar (1984) about propagation effects, Herzegh and Conway (1986) and Liu and Herzegh (1986) about sidelobe effects, Goddard et al. (1982) and knowing about the variability of the shape of raindrop size-distributions (Gori and Joss 1980), the question is unresolved as to how much improvement may be obtained by this method on an operational basis. This all means that there is hope at close ranges (with high spatial resolution) that polarisation diversity radars will give valuable information about precipitation particle distributions and other parameters pertinent to cloud physics, as reviewed by Hall (1984), but that for an application in hydrology there is still a long way to go. This is also reflected in the review by Atlas et al (1984), who summarise in their abstract about measurements of rainfall that 'these measurements are subject to potentially large errors when rainfall does not behave to apriori assumptions embodied in the technique', which we think may be quite often the case. With this statement Atlas is far less optimistic than Serafin (1987), who also descusses the application of modern radar technology in respect to multiparameter measurements of precipitation. Nevertheless Serafin does quote Zawadsky (1984), who makes clear, that the influence of Z-R relationships on the accuracy is not the dominant one.

Atlas (1984) on the other hand concludes in his 'highlights of the URSI-Symposium' that differential reflectivity ZDR-technique has shown excellent results. He believes (private communication, Aug. 1987) that 'the picture for ZDR and related polarisation methods has suddently improved with Jamson's recent work, which accounts for the effects of propagation'. He says 'that we have got to be more optimistic about it, although even this will work out to only limited ranges and can not account for the factors not related to DSD'. But this is exactly the crucial point. Of course knowing more about Z-R will help, but even if multiparameter techniques work perfectly and we could reduce the error caused by Z-R by a factor of 2 on an operational basis, as stated by Ulbrich (1984), this only means reducing a 33% error (table 2.2) to a 17% error. But for operational hydrology with radar we need to correct a much larger bias of many times this error. O'Bannon and Ahnert 1986 give for their NEXRAD-investigation a factor of four in rainfall to correct, which is on a log-scale 10 times more than the above quoted reduction by Z-R! Thus this large bias can not be caused by Z-R in the classical sense, and will not be resolved by methods estimating Z-R only!

6.4 Multiwavelength Techniques

Fujita et al (1986) compare measurements of rain rate with conventional Z-R estimates and with those obtained with multiwavelength techniques (estimates of attenuation and least square fit) and give advantages and disadvantages. Rinehart and Tuttle (1984) discuss errors resulting from antenna mismatch and alignment of beams to produce acceptable low erroneous hail signal. Rogers (1984) concludes that 'inspite of the large number of theoretical papers and proposed techniques, differential reflectivity measurements employing more than one frequency have not provided evidence of consistent and reliable hail discrimination or drop size determination'.

6.5 Measurement Of Rain From Space

Wilheit (1986) comments the passive microwave measurement from space and concludes, that 'a system exploiting the complementary strengths of visible, infrared, radar, and passive-microwave techniques would greatly improve our

ability to measure rainfall globally' (Sec.5.4).

6.6 Lidar

Atlas et al (1984) discusses the use of optical extinction to obtain additional information about particle size distribution, but note, that the method is restricted to short path length only and that fog and dust will affect situations of light rain.

7 CONCLUSIONS

7.1 Summary

Good agreement between radar and raingauges is found close to the radar (13% error for 6 hours of integration in a well defined catchment area) but strong variability and underestimation by radar occurs at longer ranges. The better Swiss radar sees on the average only 25% of the rain inspite of the fact, that it measures 100% close to the radar (Sec.4.6) because of earth curvature or shielding by topography (Sec.3.1). Similar, but not quite so dramatic results are found in flat country. In other words the main problem of using radar for precipitation measurements and hydrology in operational applications comes from the unability to measure precipitation close enough to the ground. Because of the fact that this problem is hardly detectable in well defined experiments, it did not receive the attention in the past which it deserved as a dominant problem in operational applications at longer ranges. Thanks to the availability of inexpensive, high speed data processing equipment, it is possible today to determine the echo distribution in the whole radar coverage area in three dimensions (full volume scan). It is this new knowledge together with the knowledge about the position of the radar and the orography around it, which will allow us to correct in real time for a large fraction of - or at least estimate - these errors. This correction will allow us to extend the region, in which a good accuracy is obtained, an accuracy known to us from todays well defined experiments and acceptable for many hydrological applications. To make the best possible use of radar, it may be usefull to consider the following rules:

1. Precipitation shall be estimated immediately over the ground. If this is not possible, which will be the case e.g. at longer ranges, the values have to be corrected for errors originating from the vertical profile of reflectivity (Sec.2.4). As this profile changes in time it has, for best results, to be measured continuously by the radar and the correction has to be calculated for each pixel knowing the height of the lowest visible volume above the ground (Sec.6.1).

2. It is important that this correction, being the dominant one at longer ranges, is done before any other useful adjustments are applied: Estimating Z-R relationships with various methods, taking into account advection, raingauges, etc (Sec.3.7).

3. A radar site is chosen such that precipitation close to the ground is seen by the radar (Sec.3.5). Seen means here, that there is no shielding or clutter (Sec.3.1) or that the influence of clutter can be eliminated e.g. by Doppler analysis (Sec.6.2). This condition may freqently restrict the usefull range of radar for quantitative work to the nearest 50-100 km.

4. Rigorously controlled systems are used (sufficient stability and calibration of equipment, Sec.3.6)

5. Wavelength and antenna size are reasonable: Negligible attenuation caused by precipitation (Sec.3.2) and good spatial resolution, e.g. with a 1-degree beam (Sec.3.4).

6. The data are integrated over a number of hours and/or square kilometers, i.e. adequate sample size is provided. Integration has to be done over the desired quantity (e.g. the linear rain rate, not the log(Z)) in order to avoid any bias caused by this integration (Sec.3.3).

Even a crude estimate of the actual vertical reflectivity profile will bring an important improvement, an improvement not obtainable with other means such as polarisation and multiwavelength techniques. Here the question is open, whether the additional cost and complexity justifies the gain for operational applications in hydrology. Research has to continue and to show how these new techniques have to be used in operational applications and what advantage will result. A speculation of the expected improvement of different techniques to reduce the variance of radar to estimate rain at the ground is given in the following section.

Good quantitative information is already being obtained from radars, if we consider, that rain rates are estimated over a wide range between 0.1 and over 100 mm/h. We should not forget, however, that the main advantages of radar are in the high spatial resolution, the area coverage and its immediacy (real-time data), the capability to follow a "floating target or a convective complex" in a real-time-sequence - e.g. to make a short term forecast - and that it is only to a lesser degree suited to give absolute accuracy in measuring rain amounts. It is therefore unlikely that radar will ever replace the raingauge, raingauges being essential for adjustment and checking e.g. by comparing daily amounts. On the other hand, as pointed out by many workers, we would need an extreemly dense and costly network of gauges to obtain a resolution easily attainable with radar. Furthermore there is no such easy way to get information about the vertical development of precipitation as with radar.

7.2 Estimated Improvement

In this section we try to speculate about the improvement which can be expected for hydrological applications from the various methods and additions. Obviously the exact improvement will strongly depend on the detailed conditions in which the radar is going to be used, e.g. average range, type of storm, position of the radar, parameters of the radar. As an example, just for illustrating the expected order of magnitude, we assume in Table 7.2 the case of the Swiss radars discussed in Sec.4.6 with or without mountains: Average range 100 km, rain in summer with 0 degree at 3.5 km and snow in winter, 1 degree antenna.

Nr	Measure	Improvement			
		% Gain M	% Gain F	% Cost	Reference
1	Vertical profile	70	50	5	Sec 6.1
2	Doppler radar	30	20	20	Sec 6.2
3	Measurement from space	10	20	3	Sec 6.5
4	Drop size distribution	10	10	3	Sec 2.2
5	Raingauge adjustment	5	20	5	Sec 3.7
6	Polarisation diversity	5	10	30	Sec 6.3
7	Multiwavelength radar	5	10	30	Sec 6.4
8	Lidar	1	2	5	Sec 6.6
9	1, 2, 3, 5	80	70	33	

Table 7.2: Speculations about possible influences of various measures to improve accuracy of radar for hydrological applications and the directly related cost, i.e. excluding the cost for the satellite. The gain (M for mountainous and F for flat country) is estimated as a reduction of the variance of Log(radar/gauge), assuming that the noncoherent radar today has a variance of 100%. Note, that an average improvement over the whole year and the whole area of interest is considered (max range 140 km).

The variance of a cumulation of measures (line 9) does not give the sum of the individual contributions, but something smaller, because two measures may have in part the same effect (e.g. Doppler radar and satellite to eliminate effects caused by anomalous propagation). The cost is expressed in percent of total equipment cost (hardware, software installation, maintenance, transmission and display). Note that the cost of various measures is cumulative.
Example (line 9): By combining the improvement of the vertical reflectivity profile with the Doppler option, the inclusion of satellite information (to extract artificial rain, i.e. from the clear sky) and raingauges, we find in flat country an improvement of 70%, which means that only 30% of the original variance is left. On the other hand, we have to pay for these four measures an additional 33% of the total investment. Note that in a montaneous country, because of the strong variability of parameters, some measures are expected to help more and some less than in a flat country. The above indicated variances are average, expected values in good operational conditions in the specified region. But the improvement could also be less in case e.g. the sample of the drop size distribution used to correct is no more representative for the region of interest or the added complexity of equipment leads to significantly more failures or maintenance problems.

These considerations tell us, that we should very carefully evaluate new techniques in respect to their operational feasibility, before introducing them.

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