P7.16 OPERATIONAL RAPID SCAN WEATHER RADAR SYSTEM

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1 INTRODUCTION

One of the major limitations of weather radars is their limited volume scanning time. Therefore phased array antenna and radar system technologies are receiving an increasing interest by the weather radar community. In Collier (2001) a detailed analysis of the requirements for phased arrays weather radar systems is provided. However the cost associated with phased array radars is still the major obstacle for their operational deployment.

This paper describes an advanced rapid scan strategy for operational weather radar systems featuring mechanically scanned antennas. The basis of the strategy is an interleaved volume scan. An advanced communication scheme allows a significant increase in the volume update rate. A new digital antenna drive system increases the elevation step response time of the pedestal which reduces the time required for a complete volume scan significantly. The new scan strategy is compared with the volume scan and update rates which are available from modern 3D phased array defense radars. It is shown that the dwell times which are required for accurate moment estimation are predominantly determining the volume scan time. As a consequence the update rates for meteorological scans of the phased array radar and of the proposed scanning strategy combined with an advanced mechanical drive system are comparable.

2 COMPARISON OF MECHANICALLY SCANNED AND PHASED ARRAY ANTENNA

The comparison of the performance of mechanically scanned and phased array antennas depends on the design of the phased array antenna. Modern phased array radar systems are distinguished between active and passive arrays. Active arrays are formed from a large number of transmit/receive (TR) modules connected to individual antenna elements. Passive arrays are made from antenna elements which are connected to individual phase shifters and which are sharing the same transmitter and receiver. Nowadays operational phased arrays radars are used by military services and most of them are passive arrays, having significant lower cost than active arrays.

Another differentiation of phased array radars are their scanning schemes. A flat phased array antenna aperture can only sample a limited sector in azimuth and elevation with electronic scanning. If larger sectors or even 360° in azimuth are required a multi-face or conformal array is required. Because such designs are very expensive most operational phased arrays are scanning electronically in elevation and mechanically in azimuth.

2.1 Comparison of the technical data of operational S-Band antennas

In the following two operational passive phased array antenna systems, one with mechanical azimuth scanning and one with electronic and mechanical azimuth scanning are compared with conventional weather radar antenna systems featuring 3D mechanical scanning. All antenna systems are part of the product portfolio of SELEX Sistemi Integrati.

Antenna System Type	RAT31SL	SDP10
Design	Passive phased array	2 axis mechanical scanner
Frequency	S-Band	2.7 – 2.9 GHz
Gain	39 dB	45 dB
Endfire Gain	38.9 dB	n/a
Polarization	horizontal	Dual (hor. and vert.)
Azimuth Beam Width	1.5°	1°
Endfire Azimuth Beam Width	1.52°	n/a
Elevation Beam Width	1.2°	1°
Endfire Elevation Beam Width	1.22°	n/a
El electronic scanning	±15°	n/a
Elevation tilt	15°	n/a
Az electronic scanning	n/a	n/a
Electronic Beam switching time	5 µs	n/a
Az mechanical scanning speed	36°/sec	36°/sec
El mechanical beam stepping	n/a	1.5 sec (2° ±10%)

Table 1: Comparison of S-Band Antenna Systems

Fig. 1: RAT31SL Phased Array Antenna

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Fig. 2: METEOR SLP10 Antenna System

The RAT31SL antenna system is not suited for weather radar applications. Its main limitation is the limited elevation scan capability. As with most phased array antenna systems only one polarization is possible.

2.2 Comparison of the technical data of operational C-Band antennas

Fig. 3: EMPAR Phased Array Antenna

Antenna System Type	EMPAR	CDP10
Design	Passive phased array	2 axis mechanical scanner
Frequency	C-Band	5.45 – 5.85 GHz
Gain	34 dB	45 dB
Endfire Gain (only Elevation!)	31 dB	n/a
Polarization	vertical	Dual (hor. and vert.)
Azimuth Beam Width	2.6°	1°
Endfire Azimuth Beam Width	3.7°	n/a
Elevation Beam Width	2.6°	1°
Endfire Elevation Beam Width	5.2°	n/a
El electronic scanning	±60°	n/a
Elevation tilt	30°	n/a
Az electronic scanning	±45°	n/a
Electronic Beam switching time	5 µs	n/a
Az mechanical scanning speed	360°/sec	36°/sec
El mechanical beam stepping	n/a	1 sec (2° ±10%)

Table 2: Comparison of C-Band Antenna Systems

Fig. 4: METEOR CDP10 Antenna System

The EMPAR antenna system seems well suited for meteorological scanning applications. Its only drawback is its wide beam, which is symmetrically, however. Due to its 2-axis electronic scanning capability it is possible to scan relatively large sectors where critical meteorological signatures were detected without mechanical movement of the antenna. This could be an interesting mode of operation for airports.

Both phased array antenna system will change their gain G and their beam width ϕ with the electronic scanning angle. This is inherent with all phased arrays. The degradation can be estimated from Cheston (1990):

$$G(\theta) \approx G_0 \cos\theta; \quad \phi(\theta) \approx \phi_0 / \cos\theta$$

G_0 and ϕ_0 are the “broadside” (perpendicular to array aperture) gain and beam width, respectively. The maximum electronic scanning angle is the so-called “endfire” position.

This degradation needs further consideration if phased array antennas are applied for precipitation estimation, since both figures, the gain and the beam width of the antenna are square weightened in the meteorological radar equation. Procedures must be developed for the position-dependent correction of the radar calibration.

It is also necessary to mention that the bandwidth of phased array antennas is only 50% or even less of the bandwidth of reflector antennas. This reduces the possibilities to adapt a phased array antenna to EMI threats.

2.3 *Calculation and Comparison of Volume Scan Times*

Since most weather radars are operated in networks which are dedicated to volume scanning a virtual phased array antenna featuring electronic elevation scanning is compared to a mechanical scanner. The phased array is assumed to have the same beam pattern as the antenna of the mechanical scanner.

The phased array benefits best from its capabilities if it samples the volume by successive electronic RHI scans. The azimuth rotation rate is adjusted so that an RHI scan is completed within the azimuthal beam resolution. For such a scan mode the volume scanning time T_{Vol} can be calculated from:

$$T_{Vol} = \frac{360°}{\phi[°]} \cdot N_{El} \cdot \frac{N_S}{f_{PRF}}$$

The phased array performs only one azimuth rotation during the volume scan. The rotation rate is

$$\omega_{Az} = \frac{360°}{T_{Vol}} = \frac{\phi \cdot f_{PRF}}{N_{RI} \cdot N_S}$$

The variables together with exemplary figures are listed in Table 3. The beam switching speed of the phased array is neglected since it is order of magnitude faster than that of the mechanical scanner.

The mechanical scanner samples the volume by performing a complete azimuth scan followed by an elevation step. For a complete volume it needs

$$T_{Vol} = \frac{360°}{\phi[°]} \cdot N_{El} \cdot \frac{N_S}{f_{PRF}} + T_{El}\left(N_{El} - 1\right)$$

The rotation rate of a single azimuth scan is:

$$\omega_{Az} = \frac{\phi \cdot f_{PRF}}{N_S}$$

The example shows that the phased array does not sample the volume much faster than the mechanical scanner. A mechanical scanner with a fast and precise elevation step response reduces the volume scanning time significantly. However, the slow azimuth rotation rate of the phased array reduces the scanning modulation of the radar system to an absolute minimum. Moreover, advanced sampling technologies like beam multiplexing as described in Yu (2007) can be applied with both phased array antenna systems.

Scan Parameter		**Phased Array**	**Mech. Scanner**
Beam width	ϕ	1°	
Pulse repetition frequency	f_{PRF}	1000 Hz	
Number of samples	N_S	56	
Number of elevations	N_{El}	15	
Beam switching time	T_{El}	∞	1 s
Azimuth rotation rate	ω_{Az}	1.2°/s	17.9°/s
Volume scanning time	T_{Vol}	5 min	5.4 min

Table 3: Volume scan specifications

The elevation step response time of a mechanical scanner requires further attention. Since a servo motor system has no ideal linear behaviour it is not sufficient to specify only its acceleration. The elevation step response time must be specified instead, together with a reasonable tolerance window. An example is provided in Fig. 5.

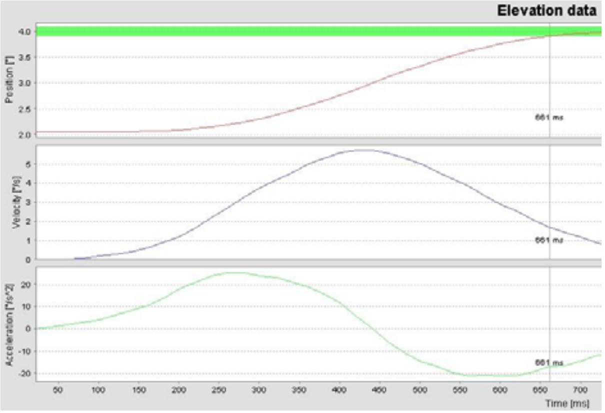

Fig. 5: 2° Elevation Step Response of the CDP10. The tolerance window is ±10% (green bar)

3 OPERATIONAL RAPID SCAN STRATEGY

Many hazardous phenomena are difficult or even impossible to characterize with conventional weather radar systems and data acquisition procedures. These limitations have long been recognized with respect to radar observations of severe weather threatening to aviation and flash flood monitoring systems. Severe weather phenomena such as tornadoes or boundary layer wind shear events, etc. evolve on time scales too short to be well observed with conventional radar scan acquisition and radar product generation logics. As a consequence the early detection of rapidly developing hazardous events requires rapid-scan radar systems. Furthermore missing information of the evolution of storm cells during conventional radar scans (eg. 3-4 rpm results in 4–6 min per 15-elevation volume) may cause significant errors. To minimize the impact on the data quality and to maximize the radar volume update cycle (and finally the provision of relevant meteorological data) several different optimizations within the radar volume acquisition and processing chain are suggested:

1) Volumetric data consist of separate PPI slices at dedicated elevation positions. These slices are acquired independently. The acquisition sequence (i.e. the sequence of particular eleva-tions) must be

flexible enough to handle different schemes (e.g. highest elevation first, lowest elevation first, etc.).

2) The radar control system as well as the radar volume composition module must be capable to handle individual PPI slice definitions, i.e. for every particular slice important performance related parameters must be adjustable. These are in general:
   - stop range, range resolution and sampling
   - trip recovery and clutter correction adjustments, i.e. signal processor related adjustments
   - dual PRF operation
   - antenna rotation speed

   Using individual settings the overall scan process can be significantly accelerated (e.g. decreasing range with increasing elevation → increasing PRF with decreasing range → increasing antenna rotation speed with increasing elevation) and exactly tailored to local conditions.
3) Volume data will be composed using individual PPI slices. Here an advanced interlacing technology will be used. Following a dedicated scheme the slices of the same or of subsequent time intervals are composed to a “virtual” volume. Intermediate volume data files can be generated (sub-volumes) and immediately forwarded to the radar product generation module.
4) The radar product generation module must be able to handle the dynamic replacement of single PPI slices in order to perform the product generation always on the newest composed “virtual” volume data available.

Based on these conditions the overall radar scan time and the radar product update interval respectively can be reduced by at least 30 – 70% without a significant impact on the meteorological data quality. Fig. 6 shows the conventional scheme comprising of a 15 elevation volume scan which usually will take appr. 5 minutes (assuming 3 rpm for reasonable velocity estimates; the antenna positioning time can be neglected, the transfer time of the volume data information between radar control processor and radar product generation module is not consid-ered). It is assumed that the elevation angles are increased with elevation number.

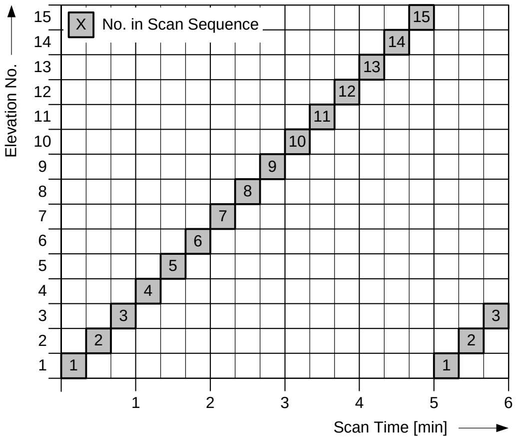

Fig. 6: Conventional 15-Elevation Scan

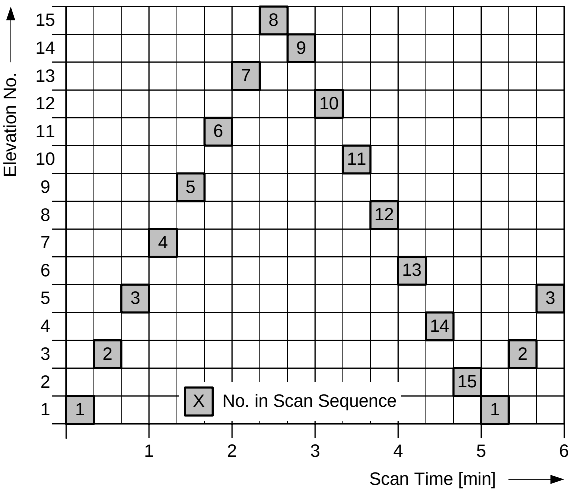

Fig. 7: Interlaced Volume Scanning

The first scan will acquire odd elevations, the second scan even elevations. The resulting volume will comprise of a composition of even and odd elevations of two subsequent scans. Disadvantages here are a possible flickering especially for low elevations with echo information in far distances and the radar product data update is still in the scope of approximately 3 min which is still quite high especially for aviation purposes.

The extended interlacing scheme foresees that:

- Dedicated elevation or elevation groups are continuously updated in every scanning cycle
- Depending on the application higher elevations are acquired firstly (e.g. to retrieve a vertical wind profile in terminal areas below 20km range) or lower elevations are scanned first (e.g. for better medium range observations determining surface rainfall or low level horizontal wind field information)
- Using the ability to replace dynamically single elevations in a virtually kept radar volume intermediate products can be generated continuously

Fig. 8 shows an example for an aviation related volume scan (high update rate for upper air vertical wind; high update for surveillance beyond terminal area and lower level; continuously update of medium levels for terminal area).

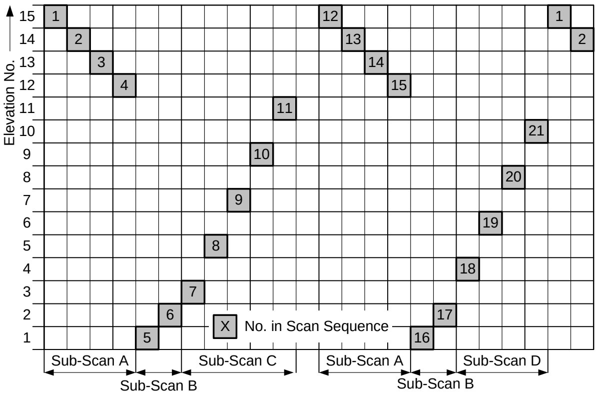

Fig. 8: Advanced Terminal Area Surveillance Scan

Each scanning cycle consists of four sub-scans. The highest four (sub-scan A) and lowest 2 elevations (sub-scan B) are updated continuously in every cycle. The interlacing consisting of sub-scans C and D is done only between elevation 3 and 11. After the completion of every sub-scan the volume data set is updated so that the complete set always consists of 15 elevations.

4 CONCLUSIONS

Modern weather radar systems with mechanical scanners featuring highly dynamic antenna drive systems, and interleaving adaptive scanning schemes are capable to provide partial volume data updates every 10-20 seconds and volume updates within about 2 minutes. Thus for the purposes of rapid volume scanning phased array antennas are not required. However phased array antennas are much more flexible with respect to the adaption to different meteorological scenarios. For instance if only specific areas of interest need to be investigated a dual-plane phased array radar will provide a much higher data update rate than a mechanical scanning radar.If there are needs to increase the volume update rate beyond the figures mentioned above phased arrays with multiple simultaneously acting apertures providing 360° electronic azimuth scanning are needed. Such systems are currently under development for military purposes. However in addition to the advanced scanning requirements such radars must provide dual polarization operation. Considering all these technical requirements the ultimate challenge will still be reaching the cost target of meteorological radars with a phased array.

5 REFERENCES

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