CARPE DIEM

Critical **A**ssessment of available **R**adar **P**recipitation **E**stimation techniques and **D**evelopment of **I**nnovative approaches for **E**nvironmental **M**anagement

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PC-based application producing predicted images of terrain and sea clutter caused by anaprop effects based on NWP model products

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1.1.1. Introduction

In this report we detail the modelling of the reflectivity display of anomalous propagation echoes based on the model outputs of thermodynamic fields from a numerical weather prediction model. This has a two-fold purpose, namely firstly of attempting to identify areas where, on the basis of prior prediction of the atmospheric state it is known to be likely to occur, and secondly, more experimentally, to help evaluate the relation between the model fields and what does occur. Identification of anomalous propagation in weather radar echoes is a vital step in quality control, without which its assimilation into NWP models would be highly problematic. The modelling represented in this work package is not intended to replace existing methods (see Alberoni et al. 2001), but to complement them. Having a physical basis on which to predicate the existence of anaprop should enable the severity in which existing methods are applied to be modified, so that excessive removal of good data does not occur in regions where clutter is unlikely.

The challenge in undertaking this task is (a) to be able to create a sufficiently good three dimensional model of the refractivity field over the domain of coverage of a weather radar – at least up to 250 km range, and (b) to implement the calculation of the propagation and scattering that is sufficiently detailed to capture the effects that lead to anomalous propagation clutter that arises in situations where negative gradients in the modified refractive index occur. Modified refractive index is a measure commonly used in the radiowave propagation literature, which adds to the physical refractive index a term that increases linearly with height, whose coefficient is the curvature of the earth. By this means, propagation can be calculated as if the geoid were locally flat; and all quantities of interest can be therefore be expressed in relation to geopotential height.

The standard method for modelling radiowave propagation in the atmosphere is known as the parabolic equation method (PEM) (see Craig and Levy 1991; Levy 1997), and is a versatile and numerically efficient method in comparison to earlier methods, such as ray-tracing and provides a full field simulation, so that field strengths do not have to be evaluated as a by-product. A particular problem with ray-tracing is that the principle of determining intensity by ray-tube cross-section breaks down in regions of focussing or caustic – phenomena that are quite likely in the kind of refractivity profiles that give rise to anomalous propagation.

The PEM can calculate the propagation factor between a real antenna and any point in the domain. For radar applications, the principle of reciprocity can also be exploited, to provide the return propagation factor for free, so that the return power to the antenna at any range gate can in principle be found by integrating the effective cross section of scatterers weighted by their propagation factors.

The principal disadvantage of the PEM is that it is necessary to sample uniformly the entire domain in which propagation takes place. This is usually no problem with modern PC's when modelling a single azimuth, but for a full radar coverage simulation, where one might wish to sample azimuths roughly every half degree, there is potentially a storage problem, and even the efficiency of the PEM is not enough to provide such a model in near real time. Because of this a new method was proposed, namely the hybrid split step method (HSSM), in which the geometry of the conventional PEM is altered so that the domain of the method can be tailored to the neighbourhood of a narrow weather radar beam.

1.1.1.1. Outline of the HSSM and comparison with the conventional PEM

The split-step technique for evaluating microwave fields propagated through an inhomogeneous atmosphere is by now an established technique that has developed over more than two decades. One of the remaining problems is that of dealing with the reflections from terrain, which has received a number of treatments refer to MacArthur and Bebbington (1991), Barrios (1994), Janaswamy (1994) and Dockery and Kutler (1996). How one deals with this problem may be considered from an application specific point of view. In many of the radar-related application domains, the motivation for such detailed propagation modelling may be attributed to the desire to find holes in the coverage of targets, usually artificial objects that may be missed if flying through an area where there is some combination of shielding or destructive interference which renders the incident field at the target so small that it may be undetected. In these cases it is imperative to model the entire field which includes the components that are reflected by the terrain as well as those incident via the refractive clear air.

By contrast, the problem of interest in this project is principally to evaluate the field strength on the terrain surface that gives rise to clutter via the anomalous propagation. The reflected field is interesting only insofar as it, too, may be refracted towards the ground to give a secondary anomalous propagation echo. As the circumstances under which this can happen are to a considerable degree restricted, it is appropriate to separate the analysis of incident and reflected waves. Moreover, the calculation of terrain backscatter cross-section in reality remains problematic. The uncertainties in determining this are still much greater than the errors that may be committed by assuming a Kirchoff approximation to the reflection, that expresses the induced surface currents in terms of the incident field alone.

Separation of the incident and reflected components of the transmitted field allows an important simplification that allows most of the advantages of the conventional PEM to be retained while gaining a great improvement in computational efficiency by reduction in spatial bandwidth. In the conventional method, the field has an angular spectrum clustered around that of angle of the wave normal to the incident field and that of the reflected field. In the conventional approach, where the field is represented by samples regularly spaced on a vertical grid, the vertical sampling must be at a sufficiently high spatial frequency to avoid aliasing. In this conventional structure, the removal of the reflected field does not in itself provide much gain. However, if the reference surface containing sample points is oriented with its normal close to that of the incident field, the non-aliasing requirements are mainly determined by the wave font curvature. One may go further, and solve the problem using curvilinear coordinates, so that a coordinate surface is more nearly aligned with the wavefront. In this case, the sampling frequency required depends not on the wave geometry, but on the spatial scales on which the refractive index profile varies. This represents a considerable relaxation on computational requirements in the atmospheric case.

The problem of changing from a rectangular coordinate system to a curvilinear one, even one of non-standard and arbitrary form is not as formidable as it might seem. An alternative view of the split-step PEM is that the Fourier transform domain part of the step (exponentiating the Laplacian) implements a convolution. The entire step is simply an approximation phase integral, with a simple form of the Green's function. By this token, efficient implementation of a split step technique in an alternative geometry can be seen as solving the problem ensuring that the phase integral can be expressed as a convolution, which means that the convolutional kernel for the phase between points on the initial and final surfaces must be expressible as a quadratic function of the difference in the transverse coordinates and furthermore, that the coefficients be constant. Although these are strong conditions, they are met in any case if the sample points are corresponding points of ray congruencies, at constant optical separation. Coordinate systems can be so constructed by ray-tracing methods, and this is the basis of the hybrid split-step technique (Fig. 1).

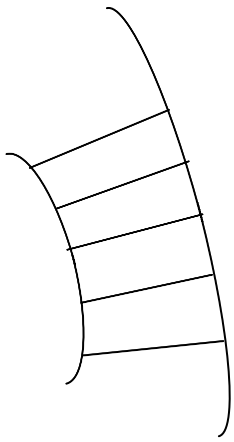


Fig. 1 – Ray congruence between two approximate wave fronts separated by a constant optical distance.

1.1.2. Applied methodologies

1.1.2.1. The hybrid split-step algorithm

The hybrid split-step algorithm was based on the premise that the wave equation for propagation in inhomogeneous medium may be simplified through the choice of a new coordinate system. Formally, the Laplacian operator is modified through the metric that expresses the optical distance in the medium. If the resulting metric is isotropic – corresponding to an isotropic optical medium, the result is a rescaling by the square root of determinant of the metric, which in a two-dimensional problem is simply the square of the refractive index. This scaling tracks the variation in the scalar component of the Helmholtz operator, leaving a wave equation that is a close approximation to that of a uniform medium. The extra terms that would be neglected in taking this approximation are those that relate to the affine connexion, or Christoffel symbols associated with derivatives of the metric. These terms are of the same order as those that are traditionally neglected in the conventional scalar wave equations that are normally adopted for the parabolic equation, as we treat a medium whose variation on the scale of a wavelength is small.

In the above description, the isotropy of the medium implies conformal symmetry, and coordinate transformations that achieve this may include any set of ray conguences. For an efficient numerical solution, the obvious choice of ray congruence is one that propagates from a known initial wavefront. In principle, a numerical solution for propagation over a finite step length might be constructed by performing ray-traces for a constant optical path step length to determine points along a new wave-front. Clearly the path step must not be so long that any rays intersect, or approach a caustic; in practice, the chosen step length will be much shorter than this.

The above prescription, though simple in essence, is not necessarily efficient. While one problem is eliminated, a new one is created: it would be necessary to perform a large number of ray-trace integrations. The key development in the hybrid split-step method lies in the fact that it is not necessary to make a coordinate transformation that exactly reproduces ray trajectories in an arbitrary refractive index profile. Rather, one can adopt a coordinate transformation that is simple, but merely close to the desired one. In that case, the resulting wave equation is still one of an inhomogeneous medium, but the gross variations in the refractive index variation are removed due to the factoring by the metric of the applied transformation. As a result, the transverse coordinate surfaces are not exact wave fronts, but surfaces on which the phase fluctuations are small. It is this key step, combined with the usual assumption that the refractive index gradients are small on the scale of a wavelength, that allows the sampling of the wave across the wave front to be reduced drastically in comparison with the conventional split-step method which propagates the solution between vertical planes.

The remaining problem is to reinstate the corresponding part of the conventional split-step method, which evaluates the path integral between points with corresponding transverse coordinates on the initial and final pseudo wave fronts. In our original formulation of the hybrid split-step method this was left to a numerical integration over each path, a factor that potentially mitigates the efficiency gain of the method. During the project we made two important technical advances for this method, which overcome this drawback. It is better to describe these in the reverse order in which they were conceived. The first problem that can be dealt with is that relating to the phase integration between the curvilinear coordinate surfaces. In principle, the problem here is that one has to know the ray path, and then apply a numerical integration to the optical distance along the ray,

$$s = \int n(r)\, dr \tag{1}$$

which may involve a number of interpolations.

One can note that, in a spatially inhomogeneous medium the ray-paths or geodesics curve because they represent the shortest (or in some cases extremal) optical distance. That curvature is apparent in the reference space in which the medium is embedded – ‘real space’. Between two points there are a number of different measures of distance that may be considered, among which are (see Fig. 2):

i. *r*, the optical distance of geometric ‘straight-line’

ii. *t*, the geometric length of the optical path

iii. *s*, the optical distance in the medium

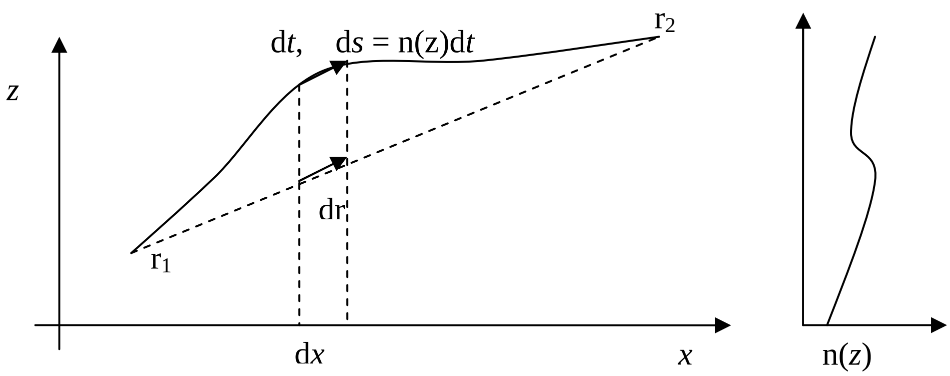


Fig. 2 – Corresponding differentials relating to the ray-path between two points in a medium.

A demonstration can be given for the paraxial case that a useful and simple relation does indeed exist, for arbitrary geodesic paths. We start with the observation of the principal law of refraction, Snell’s law, which applies equally to a continuously or piecewise discontinuous stratified medium,

$$n(z)\cos(\vartheta) = const \tag{2}$$

where ϑ is the elevation angle of a ray. In the paraxial case, a convenient way of expressing this relation, using the second order approximation to the cosine is,

$$\vartheta^2 - \vartheta_*{}^2 = n - n_* \tag{3}$$

where the star subscript refers to any convenient reference value – we let it correspond to the straight line elevation. Now we can compare the three distances,

$$
\begin{aligned}
r &= \int_{r_1}^{r_2} \left(1+\vartheta_*^{\,2}\right)^{\frac{1}{2}} n_* dx \\
t &= \int_{r_1}^{r_2} \left(1+\left(\frac{dz}{dx}\right)^2\right) dx \\
s &= \int_{r_1}^{r_2} \left(1+\left(\frac{dz}{dx}\right)^2\right) n(z(x)) dx
\end{aligned}
\tag{4}
$$

Using the approximation to Snell's law, and neglecting powers of the angles higher than second, we can express the three path differentials as,

$$
\begin{aligned}
r' &\approx \left(1+\vartheta_*^{\,2}\right)^{\frac{1}{2}}\left(1-\tfrac{1}{2}\vartheta_*^{\,2}\right)^{-1} \approx \left(1+\vartheta_*^{\,2}\right) \\
t' &\approx 1+\tfrac{1}{2}\vartheta^2 \\
s' &\approx \left(1+\tfrac{1}{2}\vartheta^2\right)\left(1+\tfrac{1}{2}\vartheta^2-\tfrac{1}{2}\vartheta_*^{\,2}\right) \approx 1+\vartheta^2-\tfrac{1}{2}\vartheta_*^{\,2}
\end{aligned}
\tag{5}
$$

From this, it is clear that the optical differential can be deduced from the geometric differential and the geometric straight line approximation, for an arbitrary profile.

This leaves the problem of integrating the optical path to one of evaluating the geometric path, which as we shall now see is easier in the context of the problem, and brings us to the second step in the analysis of the problem. In the conventional split-step approach, it would be natural to sample the refractive index gradient on a uniform vertical grid. For three-dimensional representation of the atmosphere, this would require a great deal of storage. A more efficient alternative is to construct vertical spline approximations over a polar grid, with the advantage that the density of knots in the splines can be tailored to represent features in the local vertical profiles, which are important especially in the lower part of the troposphere. At greater heights, the modified refractive index is almost linear in height and can be represented by a sparser distribution of knots. Cubic splines are generally found to be well suited to the representation of general curves of sufficient smoothness.

Given a refractivity profile represented locally by a cubic profile, it is possible to make an approximation of a ray-trajectory by considering a variational technique, based on a cubic approximation of the ray trajectory. This allows for a unique algebraic solution based on the initial height and angle of the ray. An example of this is shown in Figure 3 for a section refractivity profile representing a duct, in which the present method is compared with an accurate integration using a 4th order Runge-Kutta method.

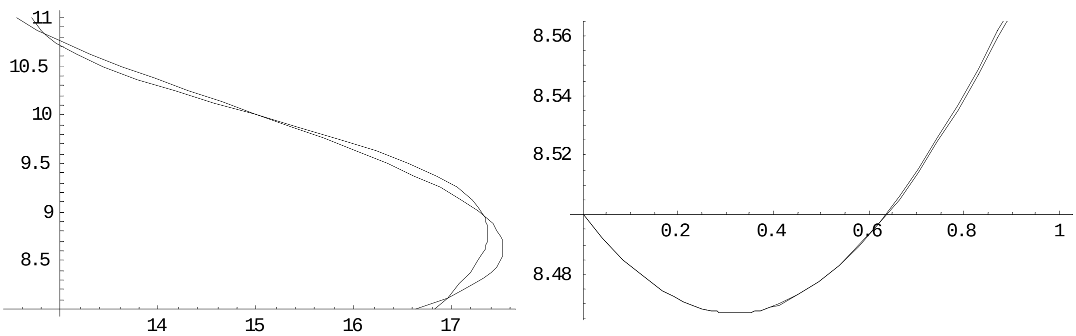


Fig. 3 – (left) A local cubic approximation to a refractive index profile (right) comparison between a direct cubic fit to the boundary conditions on the ray and the 4th order Runge-Kutta numerical integration

Computationally, it is very convenient to fix the shape of the pseudo wave-fronts as (in two-dimensional section) cylindrical. In this case, just three rays are required to fix the unique surface that includes the three points equidistant from a triad of chosen points on the source surface.

Approximations to intermediate rays may be found by uniform interpolations along the corresponding surfaces. Actual rays will in general intersect the surfaces angles that are not orthogonal. Using Snell's law, it is possible to find these angles in terms of the refractive indices at the sample points on the reference surfaces. We now use the results derived above to calculate the extra phase delay that represents the difference between the true phase integral and the geometric path, using the terminal angles to determine the geometric path length of the actual ray. The coefficients of the ray curve are determined uniquely by the position and terminal angles of the ray. It is possible to define an algebraic expression for its path length.

1.1.2.2. Reflection from terrain

The problem of reflection from the sea surface, Jha and Janaswany (2001), is not too difficult, provided it is not too rough, or the grazing angle too shallow. In practice, the anomalous propagation problem for weather radars for coverage over sea should be at grazing angle sufficiently large that a plane impedance boundary condition can be applied.

In relation to terrain, there are considerable problems to address. Using a DEM, the basic topography can be modelled, and smaller scale variation must then be modelled by some form of surface parametrization. As is well known, Long (1975), the effective criterion for roughness for reflection from terrain is that of Rayleigh, for standard deviation in surface roughness,

$$\sigma \leq \frac{\lambda}{4\pi \sin \vartheta} \tag{6}$$

where ϑ is the grazing angle. For low-angle incidence, most agricultural landscapes will appear optically smooth at C-band. To model the reflection, it is reasonable to apply a phase integral combined with a Fresnel reflection coefficient, this approximation being known as the facet model. Such a model is likely to be good provided that poles in the scattering integral, which arise from evanescent terms due to resonances, can be neglected. Examples where this might not be true would include cases where the reflection surface is of very low loss, and has highly periodic modulation, or many coupled 'cavities'. For general terrain we believe neglect of poles is likely to be safe. Evaluation of the phase integral can be expedited by considering a method of images. We developed a method that reduces this problem to a form that is very close to the basic HSSM, by consideration of the orthotomic image of a source point in the terrain profile, as shown in Figure 4.

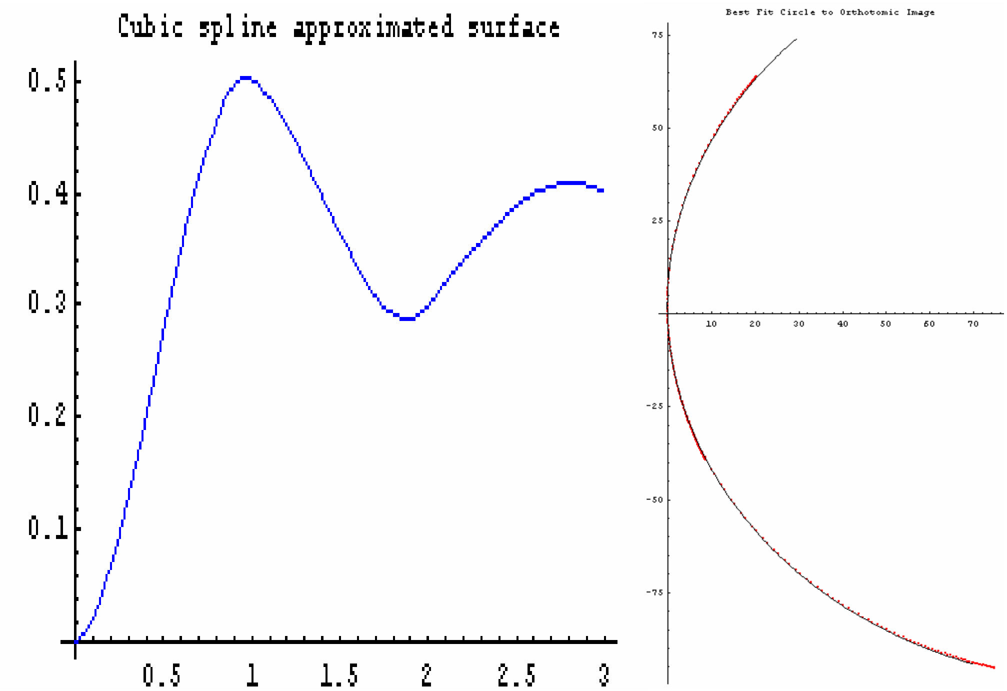


Fig. 4 – left, a model section of terrain, right a plot of orthotomic image points of a distant source tangential to the beam. The solid curve represents a best fit circle.

It is seen that even where the illuminated terrain slope varies appreciably within a range gate, the image points all lie very close to a circle. If points are distributed by weight (taking into account relative phase) and proximity to regularly spaced points, then such a surface represents a wave surface of the form required in the HSSM.

Further work is required to determine just when reflections do need to be taken into account in forward propagation. Since in practice, radiation emitted at more than about half a degree absolute elevation is highly unlikely to be refracted back to the surface, any reflections that exceed some such limit, can be automatically excluded from further consideration.

1.1.2.3. Implementation of the Anomalous Propagation Simulation Model

Implementation of the basic PC-based application was achieved by integrating a number of software modules. The computational part of the application was written in Fortran 95, and handled:

- Computation of refractive index from the NWP thermodymamic output fields
- Vertical integration from pressure coordinates to actual heights
- Interpolation of model fields to radar coordinates expressed as a polar grid
- Interpolation of a terrain elevation model to a polar grid (Fig. 5)

The last of these tasks is essentially a one-off task for any site, once the application is operational.

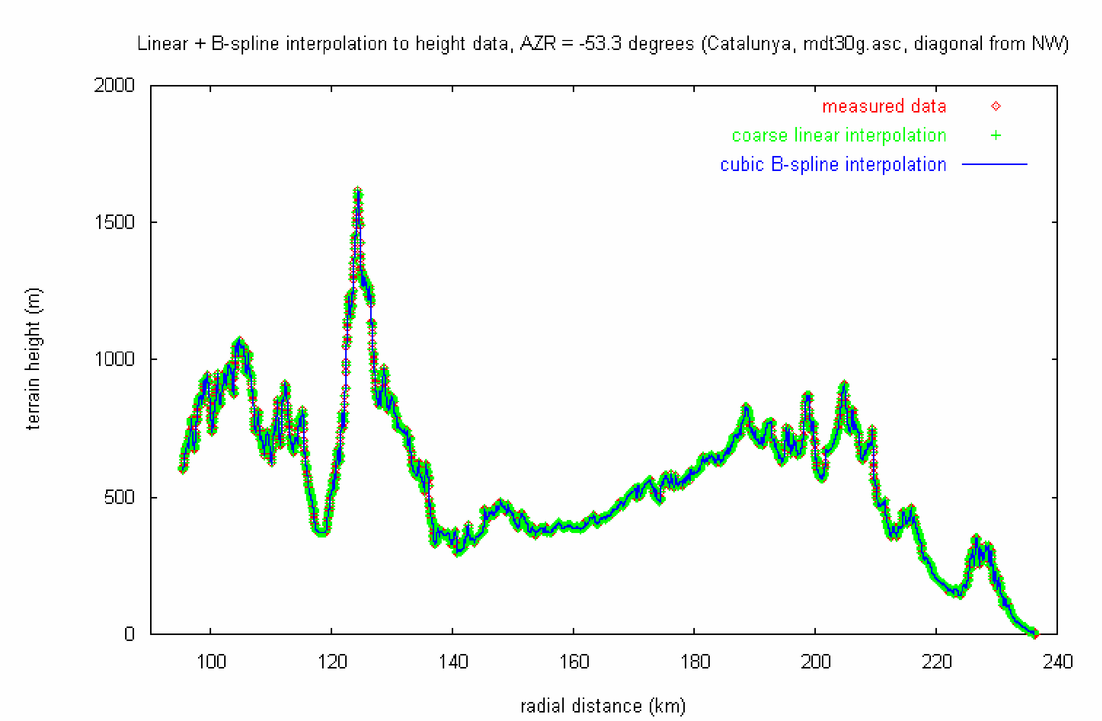


Fig. 5 – Comparison between the linearity interpolated high resolution (0.5 km) terrain elevation model grid and a B-Spline profile along the radial.

1.1.3. Scientific achievements

1.1.3.1. Spatial Interpolation of the Thermodynamic fields

Data from the numerical weather prediction model are provided on a particular geographical grid suitable for a mesoscale model, and have a sampling interval in the case we worked on of about 8 km in the centre of the grid. In terms of the tangent plane on which the radar data are projected, theses fields are not sampled on a regular grid. Moreover, for the purposes of the simulation, data are required on a polar grid. It is therefore necessary to perform some kind of interpolation.

Because of the great difference between horizontal and vertical scales, it is best to select a method for 2D interpolation of the atmospheric level sets. Since discontinuities of only a few N-units (in effect around 1% error) in the fields can give rise to image features this possibility needs to be avoided. We therefore implemented Akima interpolation, which has the properties of being smooth, and avoiding oscillatory behaviour (Fig. 6)

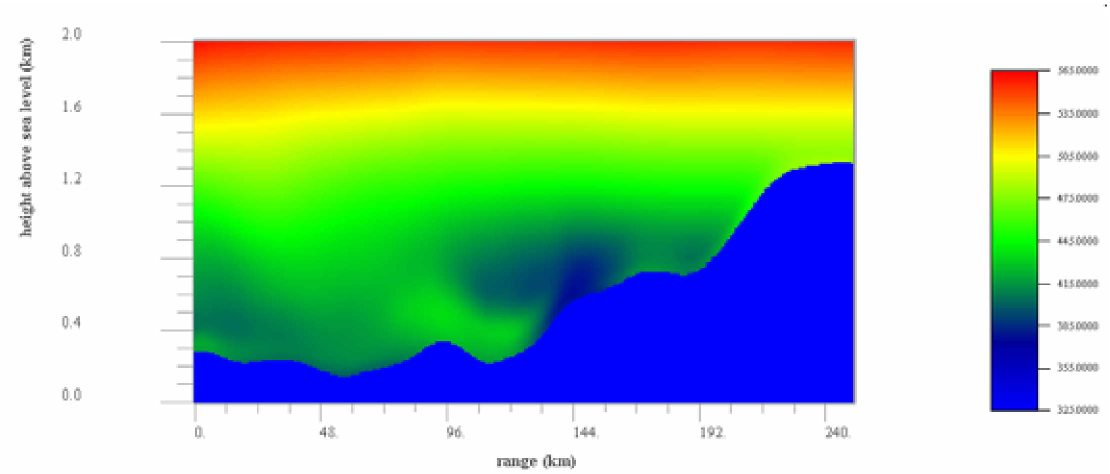
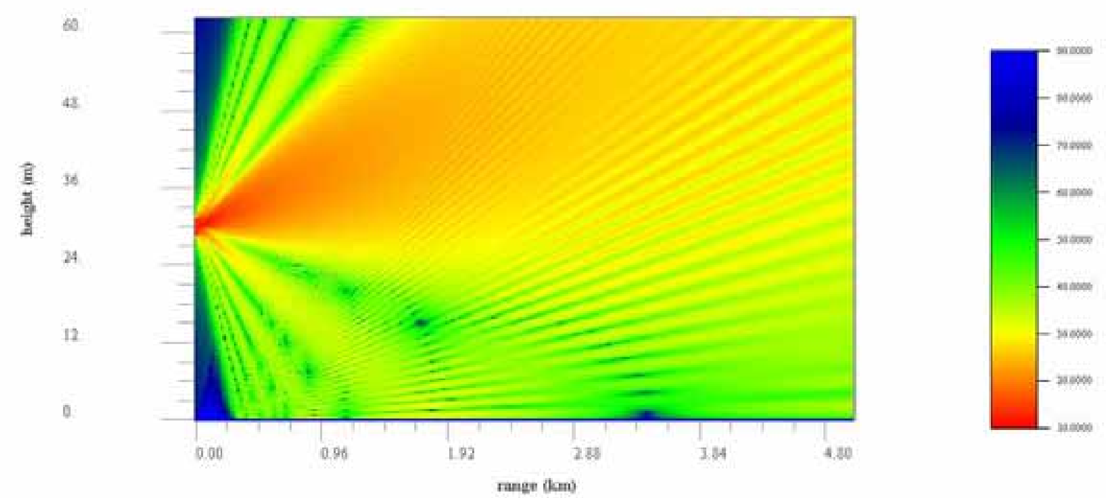


Fig. 6 – Figure shows the expected tendency towards uniform stratification at higher altitudes, but in the lower altitudes where there is interaction of the flow with the topography there is structure that may cause anomalous propagation.

Backscatter from the terrain depends sensitively on the height of the terrain, its slope, and the terrain coverage. The combined requirements of determining both height and slope in areas where the radar beam impinges on the surface mean that it is not sufficient to provide spot-heights along the radar azimuths, but to encode the height variation as a continuous curve. These considerations, along with those for efficient evaluations led to the adoption of B-spline representation of the height along each azimuth. The knots for the B-splines were obtained by means of an initial 2-dimensional interpolation from the gridded terrain elevation model. This also involved some geometric corrections from the geographical coordinates in which the terrain elevation model is expressed to those of the tangent plane centred on the radar site.

Reflectivity from terrain for natural surfaces is governed by surface roughness and the angle of incidence of the beam, usually being a power law in the grazing angle. Small variations in the relative angles can make a significant difference. Terrain coverage is also important, and where high foliage is present, the angular sensitivity is likely to be less important. At present, even good terrain databases do not provide enough information to simulate the apparent reflectivity of terrain accurately. A high level of accuracy is not strictly required, as the object of interest is not so much the magnitude as the extent of the anomalous propagation echoes. However, since weather radar echoes span a very wide dynamic range, it is natural to compare images in terms of contours of intensity, and in this respect, wide discrepancies in magnitude might be expected to give misleading results. Moreover, as our approach is inherently a physical one, the better we can model the physics of the problem, the more confidence we can have in the analysis of the results.

Tests (Fig. 7) conducted with a flat terrain under various uniform refractive index profiles show expected general patterns of field distribution, and in particular, the characteristic behaviour of ducting when an elevated reflecting layer is present.



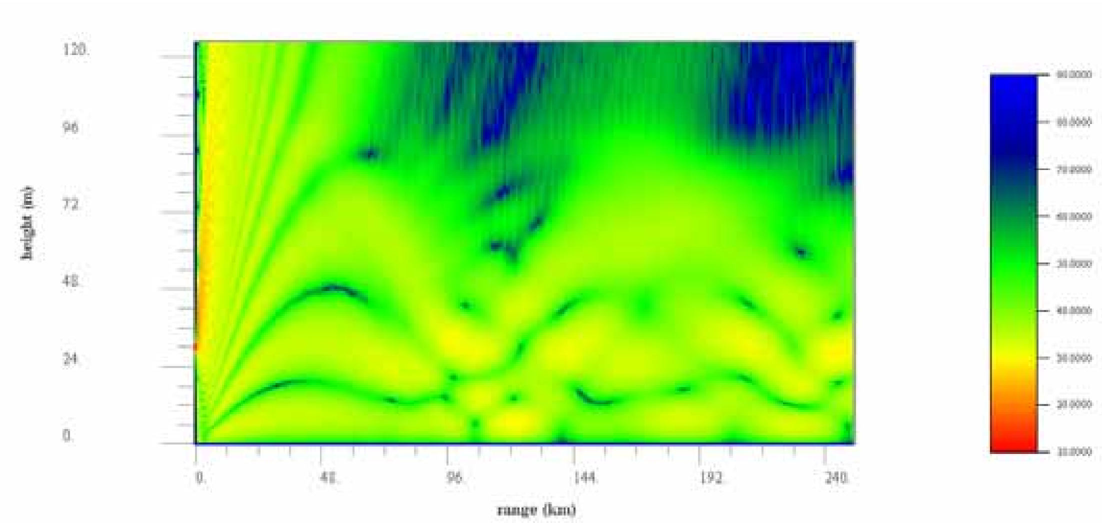


Fig. 7 – Tests of the PEM implementation over flat terrain (conformal with earth curvature). (a) above, in a normal atmosphere; fringes occur in the region of weak field outside the main beam, where energy reflected by the surface interferes with the free-space field. (b) below, with an elevated duct at 100 m; Energy at high angles is not trapped, but at low angles, the radiation pattern comprises a mixture of waveguide modes.

1.1.3.2. Real-time application combining the first application with radar data assimilation and display diagnostics

For the real time application a number of further elements were required in order to implement the fast algorithm. If the coordinate lines in the transformed space are close to the trajectories of rays (more precisely, a congruence of rays) in the physical medium, then it turns out, in a physically reasonable way, that the wave equation in the modified coordinates is only slightly perturbed in form from that of a uniform medium.

1.1.3.3. Comparison with observed radar echoes

Facilities were added to the software to enable polar displays to be produced (Fig. 8), and then complete simulations over all azimuths could be made. Unfortunately there was not enough time to be able to display both the simulated data and the images from SMC in a common format. The SMC radar data are displayed using the commercial Sigmet IRIS software. A further step that needs to be undertaken is to transform the IRIS data.

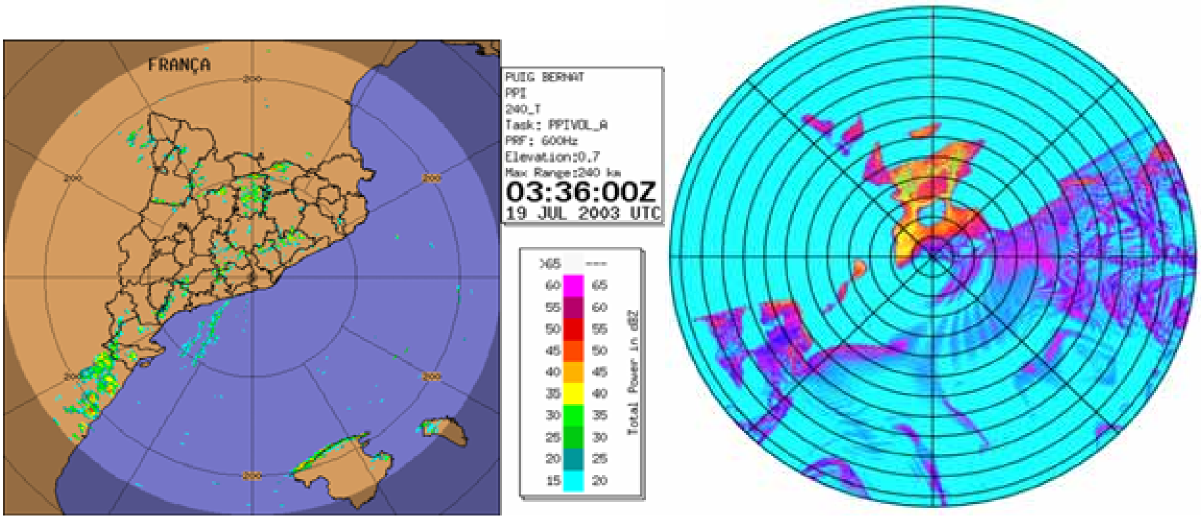


Fig. 8 – (a) observed radar image (b) Full simulation of the anomalous propagation echoes using data from the NWP model

1.1.3.4. Parallelization

F95, the language in which the software was written, incorporates several features of HPF, particularly with respect to vectorization. So, although the code was written to be able to execute serially on a single processor, where possible, either implicit or explicit vector constructs were used.

The potentials for exploiting parallelism must be considered in relation to the tasks that the software must perform. These are very disparate problems, so there is no obvious single approach to what must be done. There are a number of aspects in the software as a whole that pertain to the general problem of interpolation, some aspects of this will be remarked upon.

Data from the numerical weather prediction model are provided on a particular geographical grid suitable for a mesoscale model, and have a sampling interval in the case we worked on of about 8 km in the centre of the grid, which has to be interpolated to the polar grid of the simulation. For the sequential software package, we implemented an Akima interpolation, which is smooth, and avoids oscillatory behaviour. The downside of this was that this turned out to be a dominant component in the total computation time. The algorithm we used was written for sequential operation and had no obvious aspects that would lend it to parallelization.

While 4 x 500MHz Xeon processors represented a significant speed performance in comparison with typical PC' of two years ago, this performance, in terms of pure CPU power is eclipsed by current generation PC's of > 3 GHz. For the kind of problem we have been working on, memory bandwidth is equally important.

1.1.4. Main deliverables

Acquisition of radar data is a continuous process, and tracks phenomena that may be evolving so rapidly that even the typical 15 minute scan cycle may undersample the temporal variations. To date, assimilation has been performed according to the analysis at particular times. Elsewhere within the CARPE DIEM project the implications of continuous assimilation have been explored. If this strategy is adopted, then the rate at which radar data products are processed to achieve quality control must effectively match that of acquisition, so real time processing is potentially an important requirement.

In radar networks, processing could reasonably be performed locally, in which case the computing resources may be relatively compact. At present, multiprocessor computers remain fairly specialized, being perhaps more common in high-end servers. Recent trends towards networking of PC's have made it easier to share computing jobs between arbitrary numbers of machines. In the medium term, at least this is probably the most flexible and economic approach to running computationally intensive software with high efficiency.

The goal of producing software that can simulate anomalous propagation on the basis of predicted thermodynamic fields from a numerical weather prediction model was successfully accomplished, although the full integration of the real-time model was not complete. More work is still required to improve the efficiency, and this is principally in the area of interpolation.

The assessment of the degree to which a modest level of parallelism can be exploited is at present inconclusive, owing to the fact that although the impact is predictable and achievable in respect of some parts of the calculations carried out by our software, there remain parts where the scope for parallelism seems limited, and which at present dominate, or form a very substantial part of the total computational burden.

It may well be that, in the short term at least, a better approach would be to share the problem between networked machines. Basic PC's in small boxes with limited peripherals are now available quite cheaply, and are proving to be a cost effective way of implementing parallel or concurrent processing for a wide range of problems.

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Acronyms and abbreviations

Acronym	Explanation
DEM	Digital Elevation Model
HPF	High performance Fortran
HSSM	Hybrid Split Step Method
NWP	Numerical Weather Prediction
PEM	Parabolic Equation Model
SMC	Catalan Meteorological Service