ON THE INFLUENCE OF INCOMPLETE DATA MODELS ON ESTIMATED ANGULAR DISTRIBUTIONS IN CHANNEL CHARACTERISATION

M. Landmann*, W. Kotterman, R.S. Thomä

*Technische Universität Ilmenau, Ilmenau, Germany
Email: markus.landmann@tu-ilmenau.de

Keywords: channel characterisation, parameter estimation, antenna data model, polarimetry, artefacts.

Abstract

Despite the popularity of the use of high-resolution parameter estimation for channel characterisation and modelling purposes, the influence of the antenna data model on robustness and accuracy of the estimation has been underexposed. The point to be addressed in this paper is that the use of an incomplete data model inherently will result in biased and artificially spread angular estimates. For some antenna array types, estimation bias is even unavoidable, irrespective of the used data model. It is not inconceivable that the popular approach of clustering multi-paths components for channel modelling is spurred by the artefacts resulting from data model choices as described in this paper. Practical examples are given for two popular types of arrays, the uniform linear and uniform circular array.

1 Introduction

The impetus for the present work stems from the following observations:

1. Parameter estimation is able to achieve high resolution by incorporating a priori knowledge.
2. Part of that a priori knowledge are the data models that describe antenna responses to particular incident wave-fields, for all possible angles of incidence and all polarisation states of fields. Obviously, the use of inadequate data models precludes high-quality estimates.
3. The fact that many arrays are fitted with antenna elements that only offer one electrical input/output port is easily mistaken for insensitivity to one of the two fundamental polarisations, or for identical behaviour for both polarisations.
4. Full polarimetric calibration of antennas over 4π space angle to make up these data models is time-consuming and cumbersome, as is storage of the calibration data and handling (interpolation of) these data during estimation.
5. Therefore, often, short-cuts are taken, resulting in using a cut through the azimuthal plane and/or calibrating for one polarisation only or even not calibrating at all but relying on theoretical patterns or only partly calibrating. Table 1 gives an overview from recent literature[1], as opposed to the very few publications that use complete data models [4,5,7].
6. Linear arrays have an inherent angular response ambiguity that must lead to estimation bias.
7. Up to now, non decent treatise has been published which consequences particular choices for array types and data models have for estimation accuracy, as far as the authors are aware of.
8. As using incomplete data models during estimation may give rise to the occurrence of clusters of multi-path components where there are none, it was felt our findings will be of interest for channel modelling.

In view of the aforementioned points, we will discuss the two major effects of incomplete data models:

1. Inadequate treatment of the change of phase distributions over non-linear arrays with elevation;
2. Disregarding the fact that virtually every antenna does receive signal from both polarisation directions, by considering only array patterns for a single polarisation.

Type of experiments	Ignoring		
	Polarisation	Elevation	Polarisation + elevation
Simulations	6	1	7
Measurements	3	1	4

Table 1 Amount of publications ignoring certain aspects of antenna radiation characteristics in their data model.

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[1] To give an impression of the standing of these papers, they appeared in Transactions and Proceedings of the IEEE societies APS, CS, SPS, and VTS.

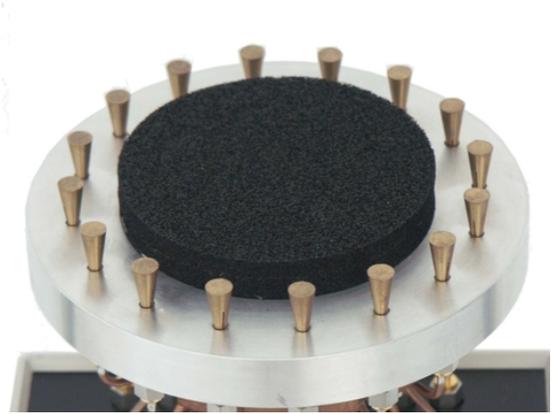Figure 1   Practical example of Uniform Linear Array

Figure 2   Practical example of Uniform Circular Array

Measurements on two popular antenna array types, the uniform linear array (ULA) and uniform circular array (UCA) will be used as illustrations.

In the following, we will use the popular terms of horizontal and vertical polarisation although the correct terms would actually be polarisation in φ and θ-direction, respectively. We distinguish between 1-D and 2-D data models, the former describing only the response in cuts in either φ (azimuthal) or θ (elevational) -plane and the latter the response over the full 4π space angle. Although using the term "elevation", the angles in the θ-direction will be expressed in co-elevation, meaning that the azimuthal plane is at 90° co-elevation and zenith at 180°, as this is more commonly used with antennas. Full polarimetric modelling in the context of this paper means that for antenna elements with only one port, the port response for both excitations (horizontal and vertical) is modelled, while for two-port elements both port responses for either polarisation are modelled (i.e. four transfers). It is also implicitly assumed that data models are derived from measured/calibrated array responses, in order not to discuss calibration and its consequences for estimation accuracy (see for instance [2]).

The structure of the paper is as follows: Section 2 treats the first effect, the changing phase with elevation and how that influences estimation of angles of incidence (or departure, for that matter), in Section 3 the effect of single polarisation antenna patterns on estimation is discussed, and Section 4 contains discussions and conclusions.

2   Phase effects of varying elevation angles

The major effect used in direction estimation with antenna arrays is the change of phase over the antenna elements with varying incident angles, both in azimuth and elevation. Additionally, amplitude effects are experienced too depending on the angular responses of the individual antenna elements of which the array is made of and on influences of the constructional parts of the array. This phase and amplitude response as function of angle of incidence is what is used by parameter estimators to match received responses to. Note that an estimator relying on element uniformity, e.g. ESPRIT, is generally not able to handle non-uniform amplitude responses over array elements, be it that in some cases additional pre-processing might relieve the problem. In contrast, this non-uniformity can in some cases even be used to advantage by Maximum Likelihood (ML)-estimators for resolving ambiguous responses. For example, if the non-uniformity is different for different elevational angles, it could be used for ML-estimation of these elevational angles. In this context, it is immaterial whether such non-uniformity stems from intrinsic responses from spatially differently oriented antenna elements or that differences between element responses are caused by coupling, fabrication tolerances, or influences of constructional parts of the array.

Although the varying phase over the array with incidence angle is the major effect routinely used in direction estimation procedures, there is a twist to it that is often overlooked. To demonstrate this, two popular generic types of arrays will be treated: the uniform linear array (ULA, Figure 1) and uniform circular array (UCA, Figure 2).

For a linear array, the phase variation along the array with varying angle of incidence is inherently linear. But as the angle of incidence is defined with respect to the axis through the array, its response shows rotational symmetry around this axis. Effectively, this means that different waves with their angle of incidence on the same cone around a ULA will impose the same phase gradient over the array, as shown in Figure 3. There will be no way of telling from the array response from where on a cone an incident wave comes. For instance, for a horizontal ULA, a wave with azimuthal incidence angle of 45° and co-elevation 90° is as likely as a wave with azimuth 90° and co-elevation 135°, resulting in 45° bias in azimuth. It is explicitly mentioned here that the directional ambiguity of linear arrays is therefore more extensive than the well-known front-back ambiguity. Intrinsically, due to the lack of aperture in the plane perpendicular to the line through the array, estimation of elevational angles of incidence with linear arrays is not feasible. The consequences of the ULA's ambiguity for direction estimation with practical ULAs will be illustrated in Section 2.1.

For a uniform circular array, the phase changes with varying angles of incidence along the array are typically not linear but sinusoidal. Here, there is less ambiguity as the phase
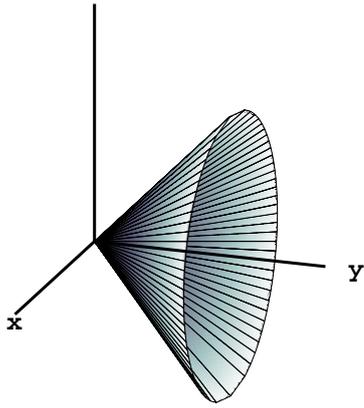
Figure 3 Waves incident on a cone centred around a ULA oriented along the y-axis, impose identical complex amplitudes.

Figure 4 Phase over 16 elem. UCA, ∅10.8 cm @5.2 GHz for incidence at different co-elevations.

gradients change with co-elevation, as shown in Figure 4. However, an upper/lower ambiguity, with the azimuthal plane as plane of symmetry, still exists. For small departures from the zero-elevation plane (co-elevation equals 90°), the effects are minor but the phase distribution over the array flattens progressively with increasing elevation until the field is normally incident on the array. Note that phase, being the argument of the complex amplitude, is a non-linear quantity and that complex amplitude distributions cannot be transformed by a single complex scalar from one phase distribution to another; on the other hand, exactly this allows to determine the elevational angle, be it less accurate where the phase changes are smallest and apart from the upper/lower ambiguity. The task of a parameter estimator is to find the complex scalar that optimally matches the incoming field to the modelled amplitude distributions, that complex scalar being the "path weight" for a component with a particular angle of incidence. When for the data model, for instance, only an azimuthal cut is available, representing the phase distribution with maximum phase gradients in Figure 4, a matching of lower gradient phase distributions, belonging to incidence outside this plane, to those of the azimuthal plane with just a single complex scalar *will* result in estimation bias and spread. This theme will be further elaborated for a practical UCA in Section 2.2.

2.1 Effect of elevation on ULA estimate accuracy

The ambiguity with ULAs for angles symmetrically around the axis of the array can be easily demonstrated by measurements on a practical ULA (Figure 1). In Figure 5, the colour depicts the estimated power distributions centred around the true angle of arrival in azimuth for horizontally and for vertically polarised waves (to the left and right, respectively). Cases for three angles of incidence are shown, -70°, -35°, and 0° in azimuth (from top to bottom) with co-elevation ranging from 20° to 160°. The picture is clipped at −25 dB, being the model accuracy as limited by residual scattering in the anechoic chamber from antenna mountings and turn-table, or by calibration inaccuracies (see e.g. [3]); the
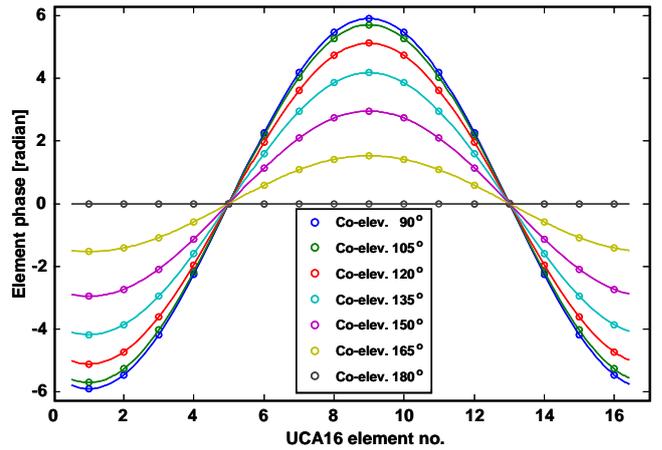
actually received power is normalised at 0 dB. With positive azimuth angles, mirror-imaged curves would result. For convenience, we used TU Ilmenau's proprietary parameter estimator, Rimax [6], but, this choice is actually immaterial: any ML parameter estimator using the same data models would render similar results. The azimuthal cut, so 1-D but full-polarimetric, was used as data model in the estimations. The effect of elevation on the bias of the angle estimation is obvious. The larger spreads on the results for vertical polarisation arise from the larger non-uniformity of the array with elevation for vertical polarisation than for horizontal, caused by differences between antenna element characteristics and different influences that constructional parts of array have on the respective properties of the individual elements. From this larger non-uniformity, larger residuals in the estimation process result when the parameter estimator approximates responses from high-tilt angles with those modelled from the azimuthal plane, these residuals in turn being interpreted as separate components.

2.2 Effect of elevation on UCA estimate accuracy

Earlier it was mentioned that the non-ambiguous phase variation over the array with elevation allows to estimate elevation but will on the other hand incur estimation errors when not properly accounted for in the data model for the estimation. Figure 6 illustrates this with measurements on the UCA shown in Figure 2. A single wave was received with the incidence angle ranging over full azimuth and elevation with its angle of incidence estimated on basis of a 1-D data model (azimuthal cut only). In order to preclude artefacts as to be described in Section 3, a full polarimetric model was used. The errors resulting from forcing the parameter estimator to estimate only one path are shown in the top part of Figure 6. The errors are large enough to render estimation results useless in our opinion, especially for the horizontal polarisation where large biases develop. The figures in the lower part of Figure 6 depict the angular spectra for the case the maximum number of paths to be estimated is increased to 10. These figures are clipped at −25 dB like in Figure 5, with
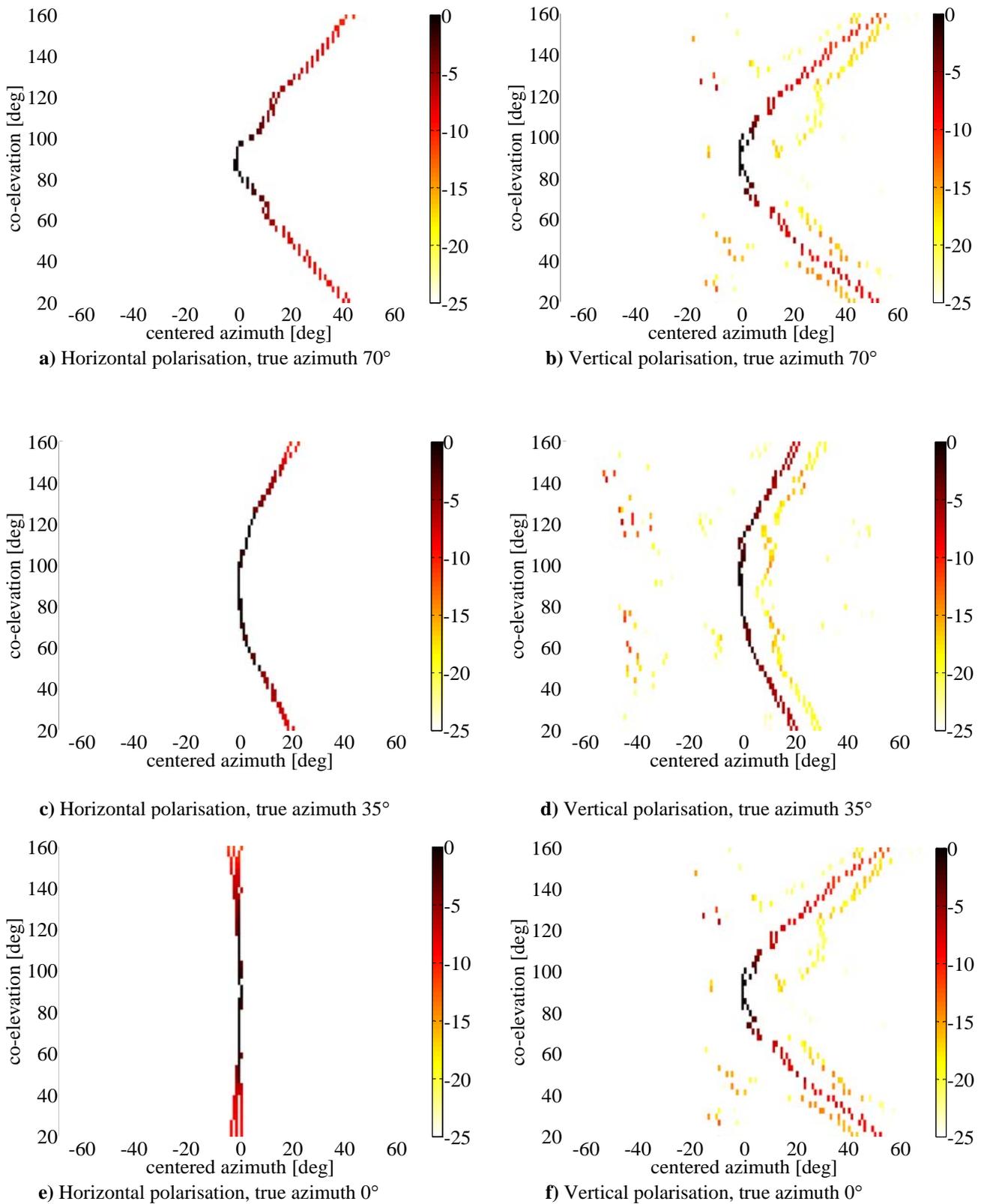
Figure 5 Measured angle estimation bias for practical uniform linear array (full-polarimetric data model used), for 3 different azimuth angles (φ=−70°, −35°, 0°, top to bottom) and two polarisations: horizontal (left) and vertical (right); co-elevation between 20° and 160°.

received power normalised at 0 dB.

It shows that reception of a single discrete component renders a number of estimated discrete components distributed around the azimuthal angle of arrival. The larger asymmetry seen for the vertical polarisation can be understood from the interaction of the ground plate of the array (Figure 2) with the changing direction of the electrical field E_θ with elevation. For horizontally polarised waves, the direction of field E_φ does not change with elevation.

As a conclusion, one does better not attempt to determine angular spreads, or cluster spreads for that matter, from parameters estimated with a 1-D data model, especially in fields with substantial specular power incident from higher elevational angles.

Although the results are specific for this particular circular array, for instance with regard to the differences in artificial angular spreads between low co-elevation and high co-elevation incidence, it may be worthwhile to remark that the occurrence of considerable spreads itself, for small angles out of the azimuthal plane, is a generic effect for circular arrays caused by the dissimilarity between the antenna response in the azimuthal plane and the antenna responses for non-azimuthal incidence.

3 Considering one polarisation only

Despite the fact that radio waves are of vectorial nature, with two independent polarisations perpendicular to the propagation direction, traditionally only the vertical component has been considered in land-mobile radio communications. With the progress of technology, the mobile radio channel has changed character drastically:

1. Carrier frequency has gone up, from VHF-band to UHF and SHF, and scattering has become increasingly important. As a result:
   a. the elevational range of incoming waves has enlarged, especially indoors and in case of over-
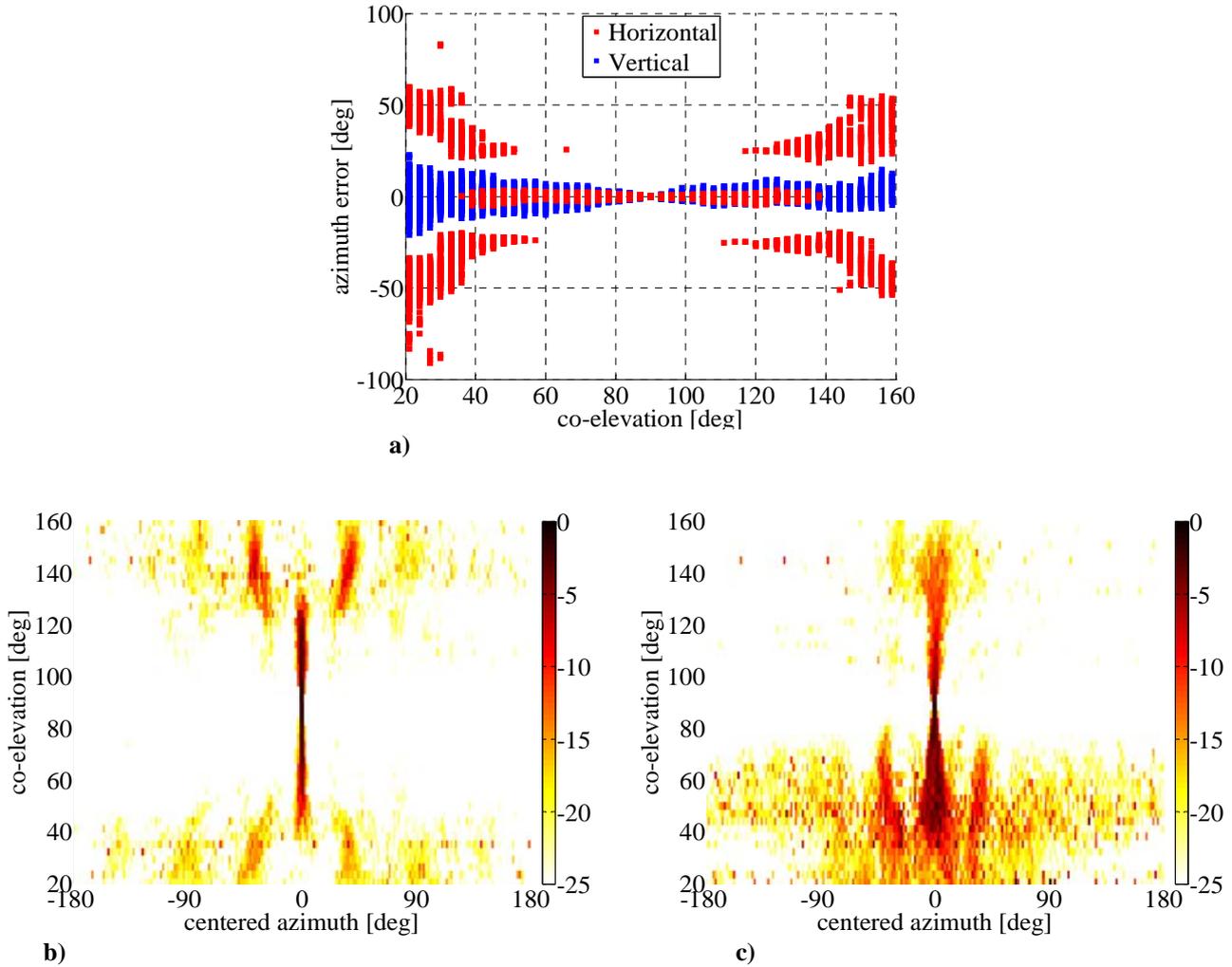

a)

b)

c)

Figure 6 Azimuthal estimation errors (top) and estimated angular power distributions (bottom) for UCA16, using 1-D (full-polarimetric) data model (azimuthal cut). Mean power distributions for horizontal polarisation (b) and for vertical polarisation (c).

rooftop propagation;

    b. in many short-range communication scenarios the polarisations will be well-mixed with the power present in both polarisations of the same order of magnitude and little correlation between the fields of both polarisations.

2. With current handheld or portable mobile communication devices:

    a. the antennas show strong polarisation cross-talk (low cross-polar discrimination (XPD) figures), meaning these antennas will receive signal from any polarisation;

    b. a fixed antenna orientation cannot be guaranteed any longer.

3. For MIMO systems, the two polarisations may provide more or less independent transfers, depending on the scattering situation, offering a welcome increase of channel rank and therefore making modelling of it worthwhile.

But, all the above-mentioned points are ignored in case in measurements, characterisation, and modelling only a single polarisation is considered, as is often still the case (see Table 1). Especially when applying parameter estimation, one should realise that for an ideal, but physically realisable antenna element, the responses to horizontally and vertically polarised fields can fundamentally never be identical. Consequently, the respective array responses cannot be either and trying to estimate the direction of incidence for one of the polarisations based on a data model for the other will result in appreciable estimation errors. The next section will illustrate this by a practical example.

3.1 Measurements for UCA, single polarisation model

The necessity of using a full polarimetric antenna model will become clear from the following comparison between using a full polarimetric (2-D) antenna model and a single polarisation (2-D) model during parameter estimation. By choosing 2-D models, the effects described in the former section are avoided. Again, the UCA depicted in Figure 2 with 16 monopoles was used for the comparison. For the data model, vertical is chosen as the single polarisation direction, as the choice of a horizontal polarisation only model was never seen in literature by the authors, but this choice is not important. The incident field is thus chosen to be a horizontally polarised wave with its angle of incidence ranging over full the azimuth and elevation. Figure 7 shows the estimated angular power distributions. On the left hand side, results for using the complete data model are shown (i.e. 2-D full polarimetric), on the right-hand side those for using the vertical polarisation pattern only. The power distributions are given as function of the deviation from the true angle of arrival (upper row: relative in azimuth, lower row, relative in elevation), clipped at -25 dB like the earlier ones. This relative depicting is possible as the variation in estimation errors

over the absolute azimuth angle is small, due to the rather homogeneous response of the UCA.

To the left, the estimated power is well concentrated around the true angle of arrival, both in azimuth and co-elevation with only little spurious. So, the intrinsic accuracy of the Rimax procedure is high, when used with full-polarimetric data models.

To the right, the results for using only the pattern for vertical polarisation show both a bias in azimuth (at the true azimuthal angle almost no power is found) and a large asymmetric bias in co-elevation. The asymmetry stems from the (vertically) asymmetric mechanical build-up of the UCA16, see Figure 2. The apparent angular spread caused by using a simplified data model, is considerable; be reminded that only a single discrete component was received.

The particular shapes of the distributions in Figure 7 are specific for the chosen array, the significant loss of accuracy in comparison with using a complete data model is not. One simply does not have control over the polarisation direction of incoming waves during measurements and with only data models for a single polarisation at hand, estimation of components with the other polarisation is bound to yield errors of type described here. Only under restrictive conditions such estimation errors could remain small. That is, when one can be sure that the array only receives a single polarisation, either because the field has a single polarisation (corresponding with the data model) or because the XPD of the antenna elements is extremely high. The former is not so likely [4] and the latter is only true for very few antenna designs within a small range of angles of incidence.

4 Discussion and conclusions

The use of linear arrays in measurements for channel characterisation poses a problem due to the inherent directional ambiguity of its response to which no solution exists. Only in cases of fields with angles of incidence confined to or close to the azimuthal plane (respectively a particular reference plane through the array line, for instance in case the array is not positioned horizontally) estimation results can be trusted. The main effect will be an elevation-dependent bias.

The front-back ambiguity can be partially remedied by shaping antenna element patterns such that the sensitivity for one half-plane is greatly reduced. For instance, with patch elements, 10 to 20 dB front-to-back discrimination can be achieved. Further reduction of the field of vision by excluding steeper angles, where bias is largest, through putting a collimator in front of the array is currently investigated by the authors. This is a principal choice when using an ULA, either correctly analysing only a part of the existing field or trying to register as many components as possible while taking the risk on distorted results.

Whereas the bias with linear arrays stems from the lack of aperture in elevation, it is the changing aperture with elevation that causes the bias and spread with arrays with
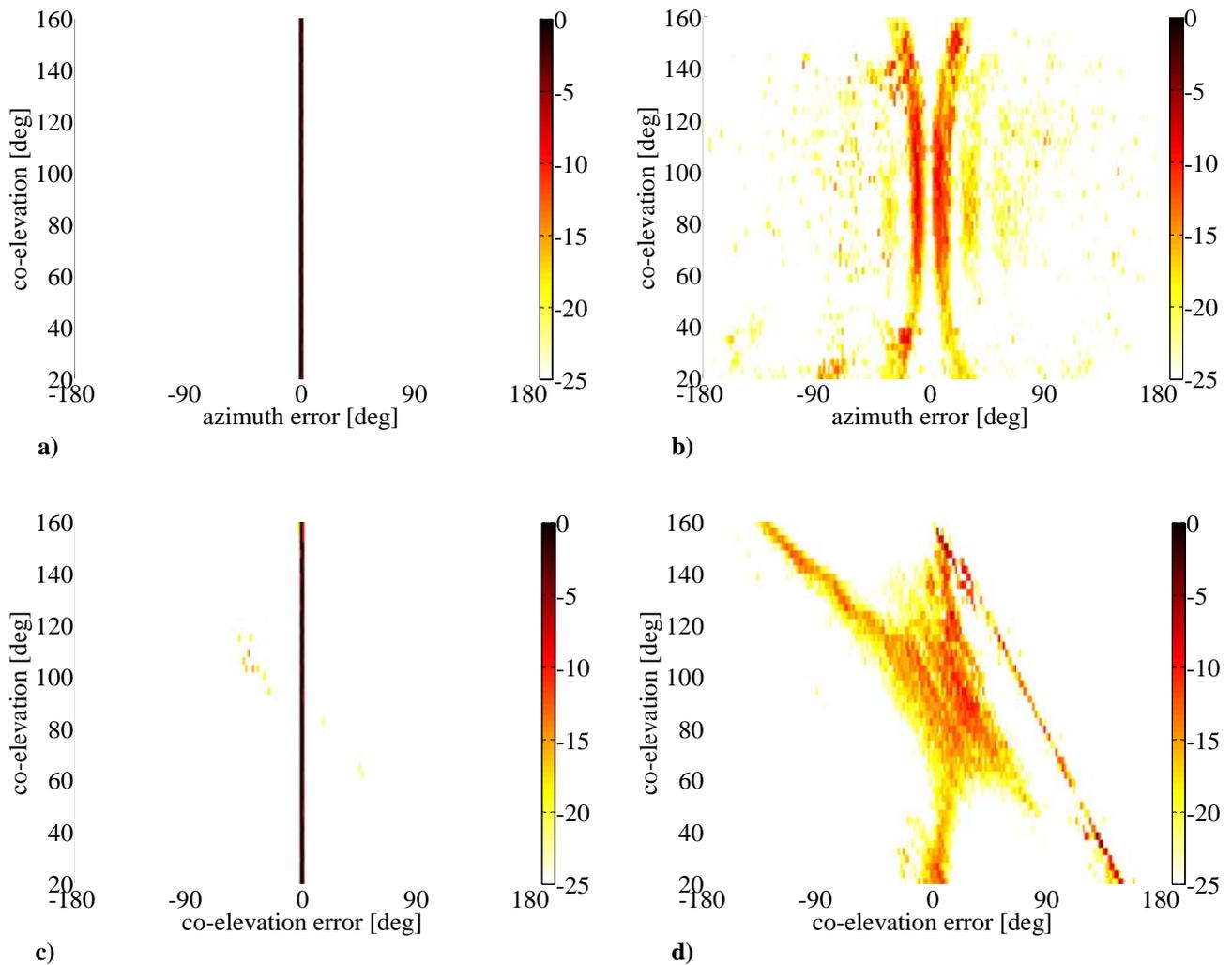
Figure 7 Comparison between parameter estimation using a full-polarimetric data model (left) and a vertical polarisation only data model (right) for reception of single horizontally polarised paths: estimated power versus deviation from true angle in azimuth (top) or co-elevation (bottom) as function of co-elevation.

more than one spatial dimension, like the circular one used in these investigations, when not considered in the data model. This too is an inherent effect. It is repeated here that, on the other hand, this elevation-dependent phase distribution is the major effect to be used for estimation of elevational angles. Optimal estimation results can be achieved by using spherical arrays, sporting an equal aperture in all directions, but, here the demand for full calibration is even stronger. than for circular arrays. Uniformity is lost on spheres as all antenna elements receive/transmit under different angles and uniform sampling is only available for the few classical/Euclidean regular polyhedron antenna arrangements.

Another important result presented here is that using data models for one single polarisation can produce serious artefacts too, both in terms of spreads and bias. Again, this is an inherent phenomenon. As with the other results, how these effects will manifest themselves depends on the particular measurement scenario and arrays.

Just as a contrast, it was shown that for the single wave scenarios considered in this paper, applying full-polarimetric 2-D data models renders very accurate estimates.

Not discussed in this contribution are for instance the effects of inadequate spatial sampling, meaning antenna elements separated by more than half a wavelength, which too can result in serious artefacts. Especially for the earlier mentioned spherical arrays, this is not trivial.

As mentioned earlier, in scenarios in which the elevational range of incoming or exiting waves is limited, without much cross-polarising scattering, the effects of using simplified data models do not need to degrade estimation accuracy seriously. These could be the less interesting scenarios, though, like an elevated base station in rural environments. On the other hand, for indoor scenarios, especially outside LoS, where rich scattering is to be

expected with potentially many components out of the azimuthal plane, the use of full-polarimetric data models incorporating the elevational array characteristics is essential. Since the paper of Bengtsson and Völcker [1], it is known that the estimation of angular spectra from irresolvable scatterer clusters using specular path models may result in angular distributions that deviate from the true ones. The point made here is that even estimation of resolvable discrete scatterer distributions will result in artificial angular distributions if not the appropriate data models for the antenna arrays are used and that estimation results for linear arrays will be inherently biased.

In channel modelling, the angular spread is an important parameter for determining the correlation an antenna array will experience. Artificial spreads, as appear from parameter estimations based on incomplete data models, portray on one hand a channel with larger spread (lower correlation) than in reality and on the other hand could well give an impression of clustered discrete components where a single strong one is actually received.

It is concluded that channel parameter estimation with imperfect data models gives rise to potentially large apparent bias and angular spreads. However, bias is unavoidable with linear arrays, even with complete data models. The authors do not rule out that clusters of scatterers published in propagation studies are partly artefacts resulting from estimations based on incomplete data models.

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