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Observability function of the Bologna - Modra forward scatter system

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Abstract. Observability function as instrumental characteristics of the Bologna - Modra forward scatter system was computed using the ellipsoidal theory described by Hines (1958). The final observability function is depicted on the contour plot as a function of the horizontal coordinates of meteor radiant positions with a step of 1°.

Key words: meteor radar – forward scatter – observability function

1. Introduction

The term 'observability function' was introduced by Hines in a couple of articles (1955, 1958). In the first paper the geometry was simplified by a cylindrical approximation of Fresnel's ellipsoids. In the second paper a more precious ellipsoidal theory was developed. After renaissance of interest in the forward scatter technique a computer program 'Forward' for calculation of the observability function based on the ellipsoidal theory was introduced by Steyaert (1987) and some modifications of the ellipsoidal theory, especially for underdense echoes, were described by Verbeeck (1997).

2. Computational method

Geometry of the forward scatter system is depicted in Fig. 1, where R_T and R_R are distances from the reflection point M to the transmitter T and receiver R, respectively. The angle 2ϕ is a forward scatter angle and τ and ρ are the angles between the axis of a meteor trail and directions to the T and R in the point M, respectively.

For a representation of geometrical parameters there was set up a cartesian coordinate system which is shown in Fig. 2. The origin of the coordinate system is identical with the midpoint of the transmitter - receiver (T-R) baseline of a length $2L$, so the coordinates of the transmitter and receiver are (-L,0,0) and (L,0,0), respectively. The orientation of the meteor trail is specified by the direction cosines (l,m,n), so the radiant position can be described using the differential azimuth φ relatively to the T-R baseline and zenith angle ϑ:

$$l = \sin\vartheta\cos\varphi, \qquad m = \sin\vartheta\sin\varphi, \qquad n = \cos\vartheta.$$

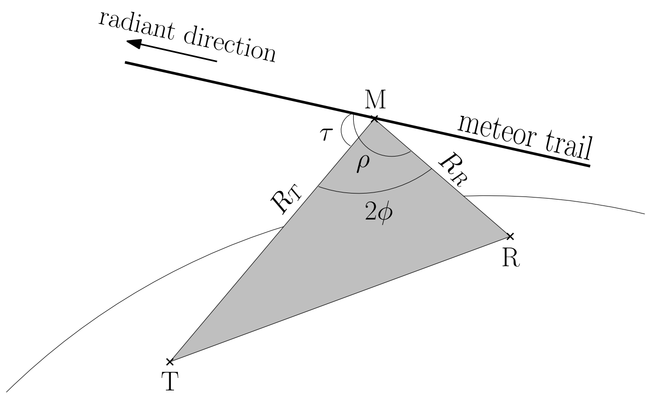

Figure 1. Geometry of the forward scatter system. R_T and R_R are distances from the reflection point M to the transmitter T and receiver R, respectively. The angle 2ϕ is a forward scatter angle and τ and ρ are the angles between the axis of the meteor trail and directions to T and R in the point M, respectively.

The ellipsoidal theory is based on an assumption of specular scattering of a radio wave. As 'potentially observable trails' are assigned only trails which fulfill the following geometrical conditions:

1. The reflection point must be visible from the locus of the transmitter and receiver.
2. The reflection point must lie within the range of the meteor zone.
3. The meteor trail must be tangent to one of Fresnel's ellipsoids, thus the angles τ and ρ must be supplementary: $\tau + \rho = 180°$.

The condition of specular scattering leads to the following system of equations:

$$\cos\tau + \cos\rho = 0, \tag{1}$$

$$\cos\tau = \Big(l(x+L) + my + nz\Big)/R_T, \tag{2}$$

$$\cos\rho = \Big(l(x-L) + my + nz\Big)/R_R, \tag{3}$$

$$R_T = \sqrt{(x+L)^2 + y^2 + z^2}, \tag{4}$$

$$R_R = \sqrt{(x-L)^2 + y^2 + z^2}, \tag{5}$$

$$z = \sqrt{(R_E + h - A)^2 - x^2 - y^2}, \tag{6}$$

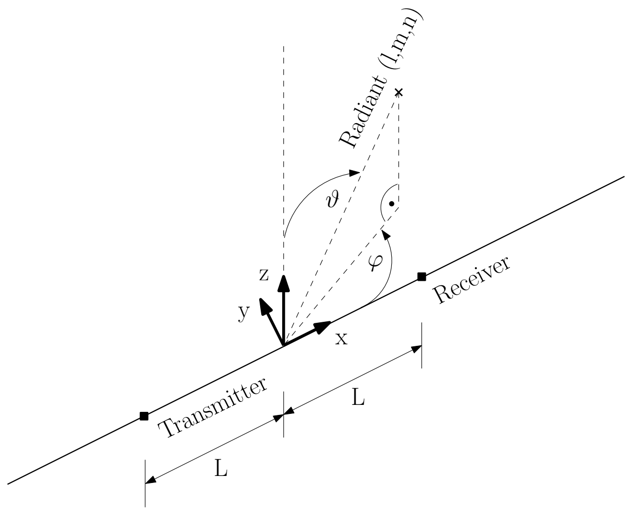

Figure 2. Coordinate system of the forward scatter setup.

where R_E is the radius of the Earth, h is the height of the reflection point and A is the distance between the origin of our coordinate system and the center of the Earth. The system of equations (1) - (6) can be rewritten for a given trail orientation (l, m, n) and h, as well as for an assumed value of y, as a polynomial equation of the 6th degree, in the form:

$$K_1 x^6 + K_2 x^5 + K_3 x^4 + K_4 x^3 + K_5 x^2 + K_6 x + K_7 = 0. \tag{7}$$

Because the forms of the polynomial coefficients (7) are complicated, they are presented in Appendix A in the Matlab language syntax. From six roots of the polynomial (7) are chosen those which are real and lie inside the boundary satisfying condition 1. The boundary was described by Verbeeck (1995) in the form:

$$|x| \leq \frac{\sqrt{(R_E^2 + L^2)(h^2 + 2R_E h)}}{R_E} - L. \tag{8}$$

The resultant pairs (x, y) define the points where specular scatterring of the signal can occur. For the given height and radiant position the points form curves. Examples of the curves are depicted in Fig. 3.

The curves of specular scattering points are computed only for one height h. However, the specular reflection can occur in a certain interval of heights. Therefore, the weighting function W_σ, which is proportional to the numerousness of the potentially observable trails for a given element $d\sigma$ of the curve, was

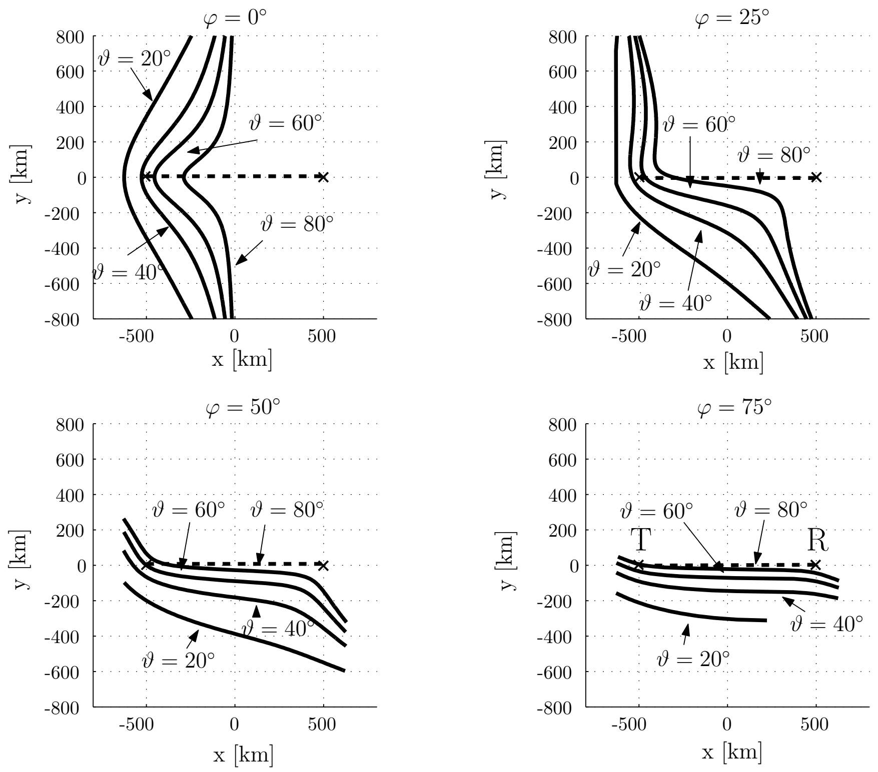

Figure 3. Examples of the curves of specular scattering points for various positions of radiants (φ, ϑ). The curves are calculated for T-R path distance of 1000 km and height $h = 100$ km. The T-R baseline is depicted by a dashed thick line.

introduced by Hines (1958). The function W_σ has the form:

$$W_\sigma d_\sigma = \frac{(R_T + R_R) sin^2(\tau) d\sigma}{R_T R_R \sqrt{[(\frac{\partial \iota}{\partial x})^2 + (\frac{\partial \iota}{\partial y})^2]}} \tag{9}$$

where $\iota = \cos\tau + \cos\rho$ and its partial derivatives are :

$$\frac{\partial \iota}{\partial y} = \frac{(m - n\frac{y}{z+A})R_T - A\frac{y}{z+A}\cos\tau}{R_T^2} + \frac{(m - n\frac{y}{z+A})R_R + A\frac{y}{z+A}\cos\tau}{R_R^2}, \tag{10}$$

and

$$\frac{\partial \iota}{\partial x} = \frac{(l - n\frac{x}{z+A})R_T - (A\frac{x}{z+A} + L)\cos\tau}{R_T^2} + \frac{(l - n\frac{x}{z+A})R_R + (A\frac{x}{z+A} - L)\cos\tau}{R_R^2}. \tag{11}$$

In order for a potentially observable trail to be really observable, it must reflect the radio signal from the transmitter with a sufficient amplitude. The amplitude of a received echo must be higher than the receiver's threshold value. A fraction of the potentially observable trails N_o that fulfill this condition is possible to express using the radar equation for underdense echoes, provided that the mean mass index of the observed particles is $s = 2$, using the form (Hines, 1958):

$$N_p \propto \cos z_R \, A_p^{-1} G_T^{\frac{1}{2}} G_R^{\frac{1}{2}} |\sin\gamma| [R_T R_R (R_T + R_R)(1 - \cos^2\beta \sin^2\phi)]^{-\frac{1}{2}},$$

where P_T is the power of the transmitter signal, G_T resp. G_R is the gain of the transmitter resp. receiver antenna in the direction of the reflection point, A_p is the threshold value of amplitude, γ is the angle between the vector of the electric field of the transmitted wave and direction to the receiver at the reflection point. For the horizontal polarization the value of $|\sin\gamma|$ can be computed applying the formula:

$$|\sin\gamma| = \frac{|y^2(1 - tan^2\delta_e) + x^2 - (L + z\tan\delta_e)^2|}{(y^2\sec^2\delta_e + [L + x + z\tan\delta_e]^2)^{\frac{1}{2}}(y^2\sec^2\delta_e + [L - x + z\tan\delta_e]^2)^{\frac{1}{2}}},$$

where $\sin\delta_e = L/2R_E$, and angles β and ϕ can be computed as follows:

$$\sin\beta = \frac{ny - mz}{\sqrt{y^2 + z^2}},$$

$$\cos 2\phi = \frac{R_T^2 + R_R^2 - 4L^2}{2R_T R_R}.$$

The numerousness of the observable trails for a given element $d\sigma$ of the curve σ is proportional to $W_\sigma N_o$, so the number of the observable trails for a given radiant position is proportional to: $\int W_\sigma N_p d\sigma$. This value is after normalisation called the 'observability function' for the given radiant direction (Hines, 1958).

3. Observability function of the Bologna - Modra forward scatter system

The forward scatter system for meteor observation Bologna - Modra is part of the BLM system (Bologna - Lecce - Modra), described by Cevolani et al. (1996). The system utilizes a continuous wave with a frequency of 42.7 MHz and peak power of 1 kW. The transmitter is located in Budrio near Bologna

$(44.6°N, 11.5°E)$ and receiver in Modra $(48.4°N, 17.3°E)$. The T-R path length of the system is 612 km.

The aerials of the transmitter and receiver are identical, 4 element Yagi mounted horizontally at a height of 1λ above ground. The elevation of the main lobe is $\approx 14°$. The combined gain factor of the transmitter and receiver antenna is depicted in Fig. 4.

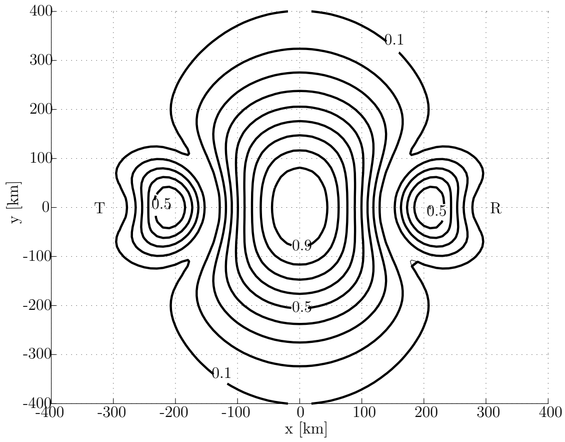

Figure 4. Combined theoretical gain factor of the transmitter and receiver antenna of the Bologna - Modra system (T-R path distance 612 km) at a 100 km height projected on the x, y plane.

The resultant observability function of the Bologna - Modra system was computed according to the method described in Sec. 2 for the network of horizontal coordinates of radiant positions with a step of 1°. The final contour plot is displayed in Fig. 5.

4. Discussion and conclusions

Although the observability function is calculated by applying the exact ellipsoidal theory, it is possible to guess some sources of errors, which affect its precision. First of all, the function is calculated using theoretical antenna diagrams, but real diagrams will be more complicated. Further, the value of the mass index of $s = 2$ is implicitly assumed. In reality the value of s is an unknown observational parameter.

A daily variation of the observability function for a given radiant can be derived from Fig. 5. For meteor showers which have dominant activity during

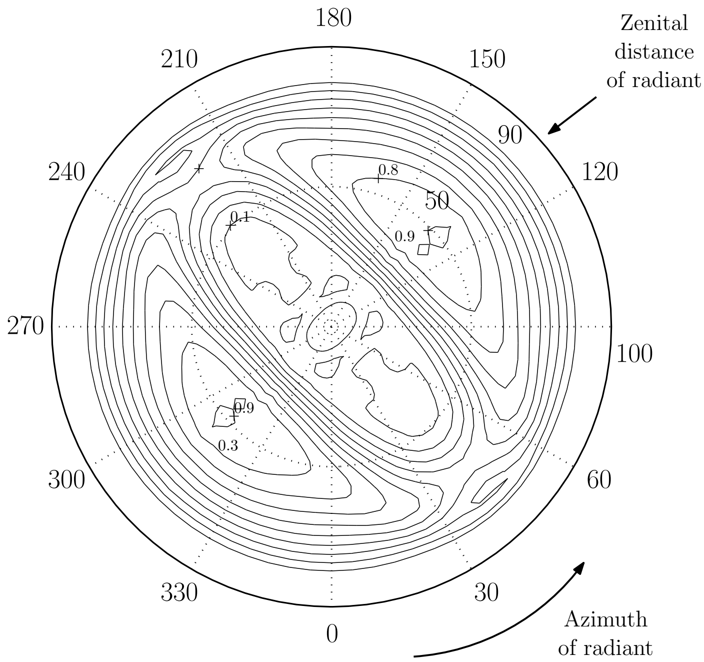

Figure 5. Observability function of the Bologna - Modra forward scatter system as a function of the azimuth and zenital distance of a radiant. The function is normalized to a maximum value of 1.

the observational period, a correlation between real daily variation of activity and daily variation of the observability function can be expected.

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A. Coefficients of the polynomial equation (7)

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%designation of variables:
%R: diameter of Earth
%h: height of reflection point
%l,m,n: direction cosines

d=2*L %T-R distance
A=sqrt(R^2 - (d^2)/4); f=(R+h)^2;

%coefficients computing
K11=0; K12=0; K13=0; K14=0;
K15=(-1/4*d^2*(-32*n^2*l^2+64*n^2*m^2)-1/4*d^2*(-32*l^2*m^2+(-4*l^2+4*m^2)^2)-8*n^2*l^2*d...
^2-8*d^2*l^2*m^2+1/2*d^2*(4*n^2-4*l^2)*(-4*l^2+4*m^2)-1/4*d^2*(4*n^2-4*l^2)^2);
K16=(-1/4*d^2*(64*m^2*n*A*l+8*l*n*A*(-4*l^2+4*m^2))+16*d^2*l*m^2*n*A-4*d^2*(4*n^2-4*l^2)*...
l*n*A-2*n*l*d^2*(8*A*l^2-8*n^2*A)+6*l*n*d^2*A*(-4*l^2+4*m^2)-1/4*d^2*((-64*A*l^2+64*n^2*A...
)*n*l+128*m^2*n*A*l));
K17=(-1/4*d^2*((32*l*m*A^2+8*d^2*l*m)*l*m+16*l^2*n^2*A^2)+(4*n^2*l^2*d^2-8*d^2*l^2*m^2)*f...
-12*l^2*n^2*d^2*A^2+12*n^2*l^2*d^2*f-2*d^2*l*m*(-4*l*m*A^2-d^2*l*m)-1/4*d^2*((8*n*l*d^2+...
96*n*l*A^2)*n*l+64*A^2*l^2*m^2)-2*n*l*d^2*(-n*l*d^2-12*n*l*A^2)-2*(8*n^2*l^2*d^2-...
4*d^2*l^2*m^2)*f);


K21=0; K22=0; K23=0; K24=(-32*n^2*l*d^2*m+4*d^2*(4*n^2-4*l^2)*l*m-4*d^2*l*m*(-4*l^2+4*m^2));
K25=(-4*d^2*(8*A*l^2-8*n^2*A)*n*m+16*n*l^2*d^2*A*m-4*d^2*(4*n^2-4*l^2)*m*n*A-1/4*d^2*(64*...
l^2*n*A*m-16*m*n*A*(-4*l^2+4*m^2)));
K26=(-48*n^2*l*d^2*A^2*m+1/2*d^2*(4*n^2-4*l^2)*(-4*l*m*A^2-d^2*l*m)-2*d^2*l*m*(4*n^2*A^2-...
4*l^2*A^2)-4*d^2*(-n*l*d^2-12*n*l*A^2)*n*m-4*d^2*(8*A*l^2-8*n^2*A)*A*l*m-1/4*d^2*((-32*n^...
2*A^2+32*l^2*A^2)*l*m+(-8*l*m*A^2-2*d^2*l*m)*(-4*l^2+4*m^2)-64*m*n^2*A^2*l)+(2*d^2*(4*n^2-...
4*l^2)*l*m+2*d^2*l*m*(-4*l^2+4*m^2)-16*n^2*l*d^2*m)*f-2*(-16*n^2*l*d^2*m+2*d^2*(4*n^2-4*...
l^2)*l*m)*f);
K27=(6*n*l*d^2*A*(-4*l*m*A^2-d^2*l*m)-1/4*d^2*((-32*l*n*A^3-8*n*l*d^2*A)*l*m+4*(-8*l*m*A^...
2-2*d^2*l*m)*l*n*A)-4*d^2*(-n*l*d^2-12*n*l*A^2)*A*l*m-2*d^2*l*m*(4*l*n*A^3+n*l*d^2*A));

K31=0; K32=0;
K33=(-16*d^2*l^2*m^2+1/2*d^2*(4*n^2-4*l^2)*(-4*l^2+4*m^2)-1/4*d^2*(-32*n^2*l^2+64*n^2*m^2)...
-24*n^2*l^2*d^2-1/2*d^2*(4*n^2-4*l^2)^2);
K34=(-6*d^2*(8*A*l^2-8*n^2*A)*n*l-12*d^2*(4*n^2-4*l^2)*n*l*A+6*l*n*d^2*A*(-4*l^2+4*m^2)+...
16*d^2*l*m^2*n*A-1/4*d^2*((-64*A*l^2+64*n^2*A)*n*l+128*m^2*n*A*l)-1/4*d^2*(-8*n*l*A*...
(-4*l^2+4*m^2)-64*m^2*n*A*l));
K35=(-4*n*l*d^2*(-n*l*d^2-12*n*l*A^2)-72*l^2*n^2*d^2*A^2-2*(-8*n^2*l^2*d^2-1/4*d^2*(4*n^2-...
4*l^2)^2)*f-2*(8*n^2*l^2*d^2-4*d^2*l^2*m^2)*f+1/2*d^2*(4*n^2-4*l^2)*(4*n^2*A^2-4*l^2*A^2)...
-1/4*d^2*(8*(-n*l*d^2-12*n*l*A^2)*n*l+(8*A*l^2-8*n^2*A)^2)-1/4*d^2*((8*n*l*d^2+96*n*l*A^2)...
*n*l+64*A^2*l^2*m^2)-2*d^2*l*m*(-4*l*m*A^2-d^2*l*m)+(8*d^2*l^2*m^2-1/2*d^2*(4*n^2-4*l^2)*...
(-4*l^2+4*m^2)+1/4*d^2*(-32*n^2*l^2+64*n^2*m^2))*f+24*n^2*l^2*d^2*f-1/4*d^2*((8*n^2*A^2-...
8*l^2*A^2)*(-4*l^2+4*m^2)-32*n^2*l^2*A^2+8*(-4*l*m*A^2-d^2*l*m)*l*m+64*m^2*n^2*A^2));
K36=(-2*(-2*d^2*(8*A*l^2-8*n^2*A)*n*l-6*d^2*(4*n^2-4*l^2)*n*l*A)*f+6*l*n*d^2*A*(4*n^2*A^2-...
4*l^2*A^2)+1/2*d^2*(4*n^2-4*l^2)*(4*l*n*A^3+l*n*d^2*A)-1/2*d^2*(-n*l*d^2-12*n*l*A^2)*(8*A...
*l^2-8*n^2*A)+(-6*l*n*d^2*A*(-4*l^2+4*m^2)-2*d^2*(4*n^2-4*l^2)*n*l*A-16*d^2*l*m^2*n*A+1/...
4*d^2*((-64*A*l^2+64*n^2*A)*n*l+128*m^2*n*A*l))*f-1/4*d^2*((8*l*n*A^3+2*l*n*d^2*A)*...
(-4*l^2+4*m^2)+4*(8*n^2*A^2-8*l^2*A^2)*n*l*A-16*(-4*l*m*A^2-d^2*l*m)*m*n*A));
K37=-12*n^2*l^2*d^2*f^2+(8*n^2*l^2*d^2-4*d^2*l^2*m^2)*f^2-1/4*d^2*(4*(8*l*n*A^3+2*l*n*...
d^2*A)*n*l*A+(-4*l*m*A^2-d^2*l*m)^2)+(-24*l^2*n^2*d^2*A^2+1/4*d^2*((8*n*l*d^2+96*n*l*A^2)...
*n*l+64*A^2*l^2*m^2)+2*d^2*l*m*(-4*l*m*A^2-d^2*l*m))*f-2*(-2*n*l*d^2*(-n*l*d^2-12*n*l*A^...
2)-36*l^2*n^2*d^2*A^2)*f-1/4*d^2*(-n*l*d^2-12*n*l*A^2)^2+6*l*n*d^2*A*(4*l*n*A^3+l*n*d^2*A);

K41=0; K42=(-32*l*n^2*d^2*m+4*d^2*(4*n^2-4*l^2)*l*m);
K43=(32*n*l^2*d^2*A*m-4*d^2*(4*n^2-4*l^2)*m*n*A-4*d^2*(8*A*l^2-8*n^2*A)*n*m);
K44=(-2*(-16*l*n^2*d^2*m+2*d^2*(4*n^2-4*l^2)*l*m)*f-64*n^2*l*d^2*A^2*m+1/2*d^2*(4*n^2-4*l...
^2)*(-4*l*m*A^2-d^2*l*m)-4*d^2*(4*n^2*A^2-4*l^2*A^2)*l*m-4*d^2*(-l*n*d^2-12*l*n*A^2)*n*m...
-4*d^2*(8*A*l^2-8*n^2*A)*A*l*m+(-2*d^2*(4*n^2-4*l^2)*l*m+16*l*n^2*d^2*m)*f);
K45=(-4*d^2*(4*l*n*A^3+n*l*d^2*A)*l*m+4*d^2*(4*n^2*A^2-4*l^2*A^2)*m*n*A+8*n*l*d^2*A*(-4*l...
*m*A^2-d^2*l*m)-16*n*l^2*d^2*A*m*f-4*d^2*(-l*n*d^2-12*l*n*A^2)*A*l*m+(-16*n*l^2*d^2*A*m+...
4*d^2*(4*n^2-4*l^2)*m*n*A+4*d^2*(8*A*l^2-8*n^2*A)*n*m)*f);
K46=((-16*l*n^2*d^2*m+2*d^2*(4*n^2-4*l^2)*l*m)*f^2+(48*n^2*l*d^2*A^2*m-1/2*d^2*(4*n^2-4*l...
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^2)*(-4*l*m*A^2-d^2*l*m)+2*d^2*(4*n^2*A^2-4*l^2*A^2)*l*m+4*d^2*(-l*n*d^2-12*l*n*A^2)*n*m+...
4*d^2*(8*A*l^2-8*n^2*A)*A*l*m)*f+4*d^2*(4*l*n*A^3+n*l*d^2*A)*m*n*A-1/2*d^2*(4*n^2*A^2-...
4*l^2*A^2)*(-4*l*m*A^2-d^2*l*m));
K47=-1/2*d^2*(4*l*n*A^3+n*l*d^2*A)*(-4*l*m*A^2-d^2*l*m)+8*n*l^2*d^2*A*m*f^2+(-6*n*l*d^2*A...
*(-4*l*m*A^2-d^2*l*m)+4*d^2*(-l*n*d^2-12*l*n*A^2)*A*l*m+2*d^2*(4*l*n*A^3+n*l*d^2*A)*l*m)*f;

KK51=(-16*n^2*l^2*d^2-1/4*d^2*(4*n^2-4*l^2)^2);
KK52=(-8*d^2*(4*n^2-4*l^2)*l*n*A-4*d^2*(8*A*l^2-8*n^2*A)*l*n);
KK53=(-64*d^2*l^2*n^2*A^2+16*n^2*l^2*d^2*f-2*n*l*d^2*(-n*l*d^2-12*n*l*A^2)-2*(-8*n^2*l^2*...
d^2-1/4*d^2*(4*n^2-4*l^2)^2)*f+1/2*d^2*(4*n^2-4*l^2)*(4*n^2*A^2-4*l^2*A^2)-1/4*d^2*(8*(-n...
*l*d^2-12*n*l*A^2)*l*n+(8*A*l^2-8*n^2*A)^2));
KK54=(8*d^2*(4*n^2*A^2-4*l^2*A^2)*l*n*A+1/2*d^2*(4*n^2-4*l^2)*(4*l*n*A^3+l*n*d^2*A)-1/2*d...
^2*(-n*l*d^2-12*n*l*A^2)*(8*A*l^2-8*n^2*A)+(2*d^2*(4*n^2-4*l^2)*l*n*A+2*d^2*(8*A*l^2-8*n^...
2*A)*l*n)*f-2*(-2*d^2*(8*A*l^2-8*n^2*A)*l*n-6*d^2*(4*n^2-4*l^2)*l*n*A)*f);
KK55=(-1/4*d^2*(-8*(4*l*n*A^3+l*n*d^2*A)*l*n*A+(4*n^2*A^2-4*l^2*A^2)^2)-1/4*d^2*(-n*l*d^...
2-12*n*l*A^2)^2+6*l*n*d^2*A*(4*l*n*A^3+l*n*d^2*A)+(24*d^2*l^2*n^2*A^2-1/2*d^2*(4*n^2-4*...
l^2)*(4*n^2*A^2-4*l^2*A^2)+1/4*d^2*(8*(-n*l*d^2-12*n*l*A^2)*l*n+(8*A*l^2-8*n^2*A)^2))*f-...
2*(-2*n*l*d^2*(-n*l*d^2-12*n*l*A^2)-36*d^2*l^2*n^2*A^2)*f+(-8*n^2*l^2*d^2-1/4*d^2*(4*n^2-...
4*l^2)^2)*f^2-12*n^2*l^2*d^2*f^2);
KK56=((-6*d^2*(4*n^2*A^2-4*l^2*A^2)*l*n*A-1/2*d^2*(4*n^2-4*l^2)*(4*l*n*A^3+l*n*d^2*A)+1/2*...
d^2*(-n*l*d^2-12*n*l*A^2)*(8*A*l^2-8*n^2*A))*f-1/2*d^2*(4*l*n*A^3+l*n*d^2*A)*(4*n^2*A^2-...
4*l^2*A^2)+(-2*d^2*(8*A*l^2-8*n^2*A)*l*n-6*d^2*(4*n^2-4*l^2)*l*n*A)*f^2);
KK57=4*n^2*l^2*d^2*f^3+(1/4*d^2*(-n*l*d^2-12*n*l*A^2)^2-6*l*n*d^2*A*(4*l*n*A^3+l*n*d^2*A))...
*f+(-2*n*l*d^2*(-n*l*d^2-12*n*l*A^2)-36*d^2*l^2*n^2*A^2)*f^2-1/4*d^2*(4*l*n*A^3+l*n*d^2*A)^2;

%coefficients of polynomial
K1=K11*y^4+K21*y^3+K31*y^2+K41*y+KK51; K2=K12*y^4+K22*y^3+K32*y^2+K42*y+KK52;
K3=K13*(y^4)+K23*(y^3)+K33*(y^2)+K43*y+KK53; K4=K14*(y^4)+K24*(y^3)+K34*(y^2)+K44*y+KK54;
K5=K15*(y^4)+K25*(y^3)+K35*(y^2)+K45*y+KK55; K6=K16*(y^4)+K26*(y^3)+K36*(y^2)+K46*y+KK56;
K7=K17*(y^4)+K27*(y^3)+K37*(y^2)+K47*y+KK57;

p= [K1 K2 K3 K4 K5 K6 K7]; %polynomial representation in Matlab
```