spec_res - An Analytic Calculation of Magnetic Spectrometer Resolutions

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April 1, 2001

Abstract

This note documents the spectrometer resolution calculation program, spec_res which computes the full error matrix, including multiple Coulomb scattering in the Gaussian limit, for an arbitrary magnetic spectrometer. The principals of the calculation and a users guide to the program including extensive examples from the present designs (proposal edition 2.0) of the CKM spectrometers are included.

1. Introduction

We recently learned that spec_res, the analytic magnetic spectrometer resolution calculator, is an invaluable tool to confirm the predictions of more complicated simulations like CKM_GEANT. Particularly we caught 30% and 10% discrepancies between spec_res and CM_GEANT in the UMS and DMS respectively. Frankly I didn't believe the calculation was this good but we now have data to the contrary.

This being demonstrated I had best document this program so that others can really use it. This note is that documentation.

2. Principals of the Calculation.

In this section I will define the notation, coordinate system and sketch the outline of the error matrix calculation. For a complete mathematical description please refer to the references given in section 2.4

2.1 Definitions and notation

The problem to be solved is to calculate the error matrix on the parameters of a charged particle trajectory in a magnetic spectrometer. Consider a single magnetic magnetic spectrometer with the magnet with a pt kick of pt_kick located at z=z_mag with a vertical field so that the bend plane is x-z and the non-bend plane is y-z. The track parameters are [X, Tx, Y, Ty,C=q/P ("track curvature")] defined at a z origin, z0. In terms of these parameters he trajectory equations are:

```
dx/dz(z)  = Tx + C*h(z-z_mag)                                  (1)

x(z)      = X  + Tx*(z-z0) + C*h(z-z_mag)*pt_kick*(z-z_mag)    (2)

dy/dz(z)  = Tx + C*h(z-z_mag)*pt_kick                          (3)

y(z)      = Y  + Tz*(z-z0)                                     (4)
```

Here h(z) is a unit step function [h(z)= {0, z<0; 1 z>=0]. Note that Tx and

Ty are actually track slopes; the tangents of the projected track angles.

The parameters is usually determined from a fit to a set of finite resolution measurements at a set of fixed z positions along the spectrometer where one coordinate of a track is measured in, for example, an MWPC plane. These measurements are taken at some azimuthal coordinate, f, where f=0 is the bend plane (x) direction and f=90 degrees the non-bend plane (y) direction. The general trajectory in the f plane is given by:

```
   c(z)      = x(z)*cos(f) + y(z)*sin(f)                                   (5)
```

Notice that with this parameterization c(z) is linear in the 5 parameters. In the usual case a track fitter starts with a list of coordinates in each (or most) of the spectrometer planes assigned by some track finding procedure to a given track and a set of constants describing the location and resolution of each plane. The determination of the 5 track parameter is a straight forward exercise in linear fitting, minimizing the chi-squared between the trajectory and the measurements in the 5 track parameters. A natural by product of the fit in the inverse error matrix which describes the uncertainty and correlations of the 5 fit parameters.

2.2 Including multiple Coulomb scattering

Introducing multiple Coulomb scattering (MCS) in the active and dead material in a spectrometer considerably complicates the calculation of the error matrix. The individual measurement are now correlated by the MCS. Consider a scatter to the left in an x measuring plane [i]. All the X measurement is subsequent plane will be displaced by Sx*(z-z[i]) where Sx is the magnitude of the MCS scattering angle and (z-z[i]) the distance between scattering plane and measuring plane. Technically this is represented by a non-diagonal covariance matrix for the measurements. They are no long independent, having been correlated by the same scatter. This "feature" turns the 29 plane DMS from a linear problem requiring the inversion of a 5x5 parameter matrix into a 29x29 double precision matrix inversion, followed by some matrix multiplication then a 5x5 inversion. Never mind, once the formulae are all correct its just more CPU time.

2.3 Limitations of the algorithm and program

The present program is limited to a single magnet with bending in the x-z plane only. This can easily be generalized if and when the need arises. The matrix computations are done if full double precision so the numerical accuracy should be more than adequate.

The trajectory is parameterized in the impulse approximation. The magnet is assumed to impart an angular change in the bend plane at the magnet mid-plane. The small angle approximation T=sin(t)=tan(T) is also assumed by the trajectory function. These will not be good approximations for real low momentum trajectories in CKM. My guess it that they are just fine to estimate the resolutions but insufficient to match upstream and downstream track segments which don't actually meet in the middle of the magnet. Consider, for example, a 90 degree bending 400 MeV/c track where the downstream and upstream segment meet at the exit face of the magnet.

The most important miss effects in this computation are the non-Gaussian tails to multiple Coulomb scattering. These, in general, don't change the standard deviations calculated by this program. They can and will have a profound affect of our backgrounds. We are going to need at least CKM_GEANT to get that piece correct.

2.4 References

The algorithm is documented in the Selex(E781) memo "Multiple Coulomb Scattering in Silicon Tracking - Addendum", Peter S. Cooper, February 27,1994 which can be found on the web at:
http://fn781a.fnal.gov/~pcooper/SVX_MS_memo.ps.gz and the PDG section on "Method of least squares - non-independent y's" Eur. Phys. C 15,197(2000).

2.5 Location of the code and recent upgrades

This code's home is on the CKM account on fnalu in ~ckm/spec_res. I've made a series of upgrades to the code for this note including:

2.5.1 made Linux compatible so I can run it at home
2.5.2 default output changed from long line to to matrix form
2.5.3 New short line output format -L
2.5.4 labels for -m d
2.5.5 man page upgraded to reflect changes

The underlying computation has not been changed.

3. User's Guide

spec_res runs interactively taking a spectrometer described in an input file and parameters, like the particle momentum, from command line switches. The standard output (written to stdout) is a table containing the error matrix for the case run scaled into convenient form and units. There are several output switches which can change or augment the output

The detailed description of a spectrometer is contained in a file (-f spec_par.ocs, by default). This file can have s set of spectrometers, each labeled with a table name (the first in the file by default, changed with the -t switch). The format of this text file is "ocs" liberated from Selex. Copy and edit what's already there or look in the man pages for details on this file's format.

3.1 spec_res options

The command line switches for spec_res are available, in usual Unix fashion, by executing the program with no switches at all.

```
<pcooper> ./spec_res
 Usage: spec_res <-c  command line output     [none]>
                 <-f  geometry file           [spec_par.ocs]>
                 <-h  header output           [none]>
                 <-l  single line output      [none]>
                 <-L  short  line output      [none]>
                 <-m  matrix output <cde>     [none]>
                 <-r  remove plane from fit   [none]>
                 <-o  geometry output         [none]>
                 <-p  particle momentum       [22. GeV/c]>
                 <-t  geometry table          [first one]>
                 <-z  z origin                [2000.]>
```

These switches control the program's input spectrometer description (f,t), the parameters which affect the computation (p,r,z), and the format of its output (c,h,l,L,m,o). Their usage is shown in the examples below.

I will stick mainly to the KEAT because it is short and illustrative. Note that all these examples are my best present understanding the the spectrometers designs in the second edition of the proposal (April 2, 2001). The results are meaningful in that context too.

3.2 A simple example

Let's first take the simplest example; the KEAT using all the defaults.

```
<pcooper> ./spec_res -o -c -t keat_mwpc
#keat_mwpc     0     0 fill anal v01.00 23-Mar-2001 23:00 psc ! KEAT parameters

name        material        z     phi      hz      xl     res  ptkick
keat_1x     mwpc       1179.0      0.     0.3  .00089  .0115   0.
keat_1u     mwpc       1180.0     60.     0.3  .00033  .0115   0.
keat_1v     mwpc       1181.0    -60.     0.3  .00089  .0115   0.
he_bag_6    helium     1320.0      0.   159.0  .00090  .0      0.
keat_2x     mwpc       1499.0      0.     0.3  .00089  .0115   0.
keat_2u     mwpc       1500.0     60.     0.3  .00033  .0115   0.
keat_2v     mwpc       1501.0    -60.     0.3  .00089  .0115   0.

spec_res -o -c -t keat_mwpc
  planes     sx     stx      sy     sty
            [um]  [mRad]    [um]  [mRad]
      3F    335.   0.976   0.000   0.000
                   0.047   0.000   0.000
                            335.   0.976
                                   0.047
```

This run is for a 22 GeV particle (-p 22.[GeV/c]is the default) with the default origin (-z 2000. [cm]). For output I selected the command line (-c) and the spectrometer table (-o). My file has several spectrometers:

```
<pcooper> grep ^# spec_par.ocs
#ums_air       0     0 fill anal v01.00 24-Mar-2001 12:00 psc ! UMS parameters
#ums_mwpc      0     0 fill anal v01.00 24-Mar-2001 12:00 psc ! UMS parameters
#keat_mwpc     0     0 fill anal v01.00 23-Mar-2001 23:00 psc ! KEAT parameters
#ums_ssd       0     0 fill anal v01.00 24-Aug-2000 23:00 psc ! UMS parameters
#dms_straw     0     0 fill anal v01.00  1-Sep-2000 11:50 psc ! DMS parameters
#selex_vx      0     0 fill anal v01.00 31-Aug-2000 08:30 psc !
#selex_vx_res  0     0 fill anal v01.00 31-Aug-2000 08:30 psc !
#test          0     0 fill anal v01.00 24-Aug-2000 23:00 psc !
```

so I had to specify which one I wanted with the -t switch.

The default output error matrix is scaled into standard deviations for the diagonal elements (in microns and milliradians and % for sp/p). The off diagonal elements as scaled into linear correlation coefficients rho(ij)=s(ij)/sqrt(s(ii)s(jj)). These are dimensionless numbers between -1 and 1 which measure how correlated two parameters are. rho=-1 means a a 1 sigma change in the first parameter causes a -1 sigma change in the second in order to re-minimize chi-squared. Uncorrelated variables have rho=0 The "planes" variable is a bit mask (in hex) with one bit set for each plane included in the fit. In this case there are 6 planes, the first measuring plane is '01'x, the last '20'x. They are all are included so planes='3F'x.

3.2 Removing MCS

The same case with no multiple Coulomb scattering can be simply done by just running a very large momentum beam since MCS goes like 1/P.

```
<pcooper> (./spec_res -h -l -t keat_mwpc ;./spec_res -l -t keat_mwpc -p 220.;
           ./spec_res -l -t keat_mwpc -p 2200.)
  planes      sx  r_xtx   r_xy  r_xty    stx r_tx_y r_txty      sy  ry_ty    sty
            [um]                      [mRad]                  [um]         [mRad]
      3F    335.  0.976  0.000  0.000  0.047  0.000  0.000    335.  0.976  0.047
      3F    283.  0.972  0.001  0.000  0.042  0.000  0.000    282.  0.972  0.042
      3F    282.  0.972  0.001  0.000  0.041  0.000  0.000    282.  0.972  0.041
```

Here I ran 3 times with ten times bigger momentum each time and chose the one line output format (-l) with a header the first time (-h) to make a table of cases as a function of momentum. The contribution of MCS in the KEAT takes a measurement only angular resolution of 41 microradians to 47 microradians.

3.3 Moving the origin

Shifting the z origin will change the position resolution and the correlations between position and angles.

```
<pcooper> ./spec_res -h -l -t keat_mwpc -z 5000.
  planes      sx  r_xtx   r_xy  r_xty    stx r_tx_y r_txty      sy  ry_ty    sty
            [um]                      [mRad]                  [um]         [mRad]
      3F   1737.  0.999  0.000  0.000  0.047  0.000  0.000   1737.  0.999  0.047
```

In this case, where I've moved the KEAT origin to the middle of the DMS (50m), note that sx has increased about 5 times from 335 [um] to 1735 [um] and that the linear correlation coefficients r_xtx and r_yty have saturated at 0.999 from 0.972.

Conversely, if I move the origin to the middle of the KEAT the position and angular measurements are correlated only my MCS in the first station. This gives the "intrinsic" position resolution of the spectrometer, with no contribution to the uncertainty from the angular uncertainty.

```
<pcooper> ./spec_res -h -l -t keat_mwpc -z 1320.
  planes      sx  r_xtx   r_xy  r_xty    stx r_tx_y r_txty      sy  ry_ty    sty
            [um]                      [mRad]                  [um]         [mRad]
      3F     74.  0.099  0.000  0.001  0.047  0.001  0.000     74.  0.094  0.047
```

3.4 Removing measurements from the fit

The -r switch can be used to remove one or more measurements from the fit to study cases where a plane is inefficient, etc. This switch is a bit tricky. It removes any element of the spectrometer whose name matches the string given to it. There can be multiple -r switches on a command line. For example -t ums_mwpc -r keat removes all the keat planes from the UMS fit. For a measuring plane the measurement is remove but the MCS from the material in that plane remains. It gets demoted by -r to a passive multiple scatterer. For passive material a -r match removes the material. For example -t ums_mpwc -r he remove the MCS from the helium bags. The names of removed elements in

```
a -o output are marked with a *.  Some KEAT examples follow:


Removing the helium bag

fnppd:spec_res> ./spec_res -o -h -L -t keat_mwpc -r he ;
                ./spec_res       -L -t keat_mwpc

#keat_mwpc     0     0 fill anal v01.00 23-Mar-2001 23:00 psc ! KEAT parameters

name         material        z     phi      hz       xl     res  ptkick
keat_1x      mwpc       1179.0      0.     0.3  .00089  .0115   0.
keat_1u      mwpc       1180.0     60.     0.3  .00033  .0115   0.
keat_1v      mwpc       1181.0    -60.     0.3  .00089  .0115   0.
he_bag_6*    helium     1320.0      0.   159.0  .00090  .0      0.
keat_2x      mwpc       1499.0      0.     0.3  .00089  .0115   0.
keat_2u      mwpc       1500.0     60.     0.3  .00033  .0115   0.
keat_2v      mwpc       1501.0    -60.     0.3  .00089  .0115   0.

  planes    sx      stx     sy      sty       p      z
           [um]   [mRad]   [um]   [mRad]  [GeV/c]  [cm]
      3F    335.   0.047    335.   0.047    22.0   2000.
      3F    335.   0.047    335.   0.047    22.0   2000.

Removing the the first plane

fnppd:spec_res> ./spec_res -o -h -L -t keat_mwpc -r 1x
#keat_mwpc     0     0 fill anal v01.00 23-Mar-2001 23:00 psc ! KEAT parameters

name         material        z     phi      hz       xl     res  ptkick
keat_1x*     mwpc       1179.0      0.     0.3  .00089  .0115   0.
keat_1u      mwpc       1180.0     60.     0.3  .00033  .0115   0.
keat_1v      mwpc       1181.0    -60.     0.3  .00089  .0115   0.
he_bag_6     helium     1320.0      0.   159.0  .00090  .0      0.
keat_2x      mwpc       1499.0      0.     0.3  .00089  .0115   0.
keat_2u      mwpc       1500.0     60.     0.3  .00033  .0115   0.
keat_2v      mwpc       1501.0    -60.     0.3  .00089  .0115   0.

  planes    sx      stx     sy      sty       p      z
           [um]   [mRad]   [um]   [mRad]  [GeV/c]  [cm]
      3E    395.   0.063    335.   0.047    22.0   2000.

Removing  two planes
fnppd:spec_res> ./spec_res -o -h -L -t keat_mwpc -r 1x -r 2v
#keat_mwpc     0     0 fill anal v01.00 23-Mar-2001 23:00 psc ! KEAT parameters

name         material        z     phi      hz       xl     res  ptkick
keat_1x*     mwpc       1179.0      0.     0.3  .00089  .0115   0.
keat_1u      mwpc       1180.0     60.     0.3  .00033  .0115   0.
keat_1v      mwpc       1181.0    -60.     0.3  .00089  .0115   0.
he_bag_6     helium     1320.0      0.   159.0  .00090  .0      0.
keat_2x      mwpc       1499.0      0.     0.3  .00089  .0115   0.
keat_2u      mwpc       1500.0     60.     0.3  .00033  .0115   0.
keat_2v*     mwpc       1501.0    -60.     0.3  .00089  .0115   0.

  planes    sx      stx     sy      sty       p      z
           [um]   [mRad]   [um]   [mRad]  [GeV/c]  [cm]
      1E    431.   0.066    447.   0.059    22.0   2000.
```

Notice that the program is smart enough to handle a singular matrix like this case (4 parameter and only 4 measurements.) Remove one more and you get:

```
fnppd:spec_res> ./spec_res -h -L -t keat_mwpc -r 1x -r 2u -r 2v
  planes    sx      stx     sy      sty       p      z
           [um]   [mRad]   [um]   [mRad]  [GeV/c]  [cm]
       Enan     nan     nan     nan         22.0   2000.
```

Miracles it doesn't do!

3.5 Additional output matrices

The program will optionally write out three matrices under the control of the -m switch. The full inverted measurement correlation matrix (n x n for an n plane spectrometer) is controlled by the -m c switch. The derivatives of the parameters with respect to the measurement (dP[i]/dc[k]) is controlled by the -m d switch. The actual parameter error matrix, in natural program units ([cm],[radians], [1/GeV]) is controlled by -m e switch. The switches can be combined; -m cde prints all three matrices. AN example using the KEAT follows. I have annotated the output.

```
fnppd:spec_res> ./spec_res -h -L -t keat_mwpc -m cde
  planes    sx      stx     sy      sty       p      z
           [um]   [mRad]   [um]   [mRad]  [GeV/c]  [cm]
      3F    335.   0.047    335.   0.047    22.0   2000.

! -m c - measurement correlation matrix

    7.56E+03    0.00E+00    0.00E+00    0.00E+00    0.00E+00    0.00E+00
    0.00E+00    7.56E+03    8.78E-03    -1.1        -2.1         1.1
    0.00E+00    8.78E-03    7.56E+03    -2.5         2.5        -5.0
    0.00E+00    -1.1        -2.5        5.76E+03   -9.07E+02   -9.08E+02
    0.00E+00    -2.1         2.5       -9.07E+02    5.74E+03    9.09E+02
    0.00E+00     1.1        -5.0       -9.08E+02    9.09E+02    5.73E+03

!  -m d parameter / measurement derivative matrix

name              dx/dc      dtx/dc       dy/dc      dty/dc       dC/dc
                 [um/um]   [mrad/um]     [um/um]   [mrad/um]      [/um]
keat_1x        -1.05E+00   -2.09E-04    2.29E-03    4.26E-07
keat_1u        -5.17E-01   -1.03E-04   -9.04E-01   -1.81E-04
keat_1v        -5.16E-01   -1.03E-04    8.98E-01    1.80E-04
keat_2x         1.71E+00    2.08E-04    3.01E-03    3.68E-07
keat_2u         8.59E-01    1.05E-04    1.48E+00    1.80E-04
keat_2v         8.58E-01    1.05E-04   -1.48E+00   -1.81E-04

! -m e parameter error matrix

    1.12E-03    1.53E-06    4.32E-07    1.57E-10
    1.53E-06    2.20E-09    1.57E-10   -4.96E-13
    4.32E-07    1.57E-10    1.12E-03    1.53E-06
    1.57E-10   -4.96E-13    1.53E-06    2.21E-09
```

The measurement correlation matrix shows the correlations (the off diagonal matrix elements) in the measurement due to MCS for all measurements after the first.

The parameter - measurement derivative matrix shows the change in parameters for a unit change in any particular measurement in the fit. For example, dtx/dc[1x] = -2.09E-04 [mrad/um]. Since the KEAT wire spacing is 800 [um] this means that assigning the wrong wire by one in the first chambers to a track will pull Tx by -2.09E-04 [mrad/um] * 400 [um] = -0.084 [mrad] or nearly 2 sigma, better to do the pattern recognition correctly.

The parameter error matrix is just the unscaled version of the standard output (e.g. sqrt(1.12E-03) = 0.0335 [cm] = 335 [um]).

4.0 Resolutions for Each for the V2.0 CKM Spectrometers

I have run spec_res here on each of the three tracking spectrometer, UMS KEAT and DMS both for a nominal 22 GeV/c beam and as a function of momentum over the relevant range. In each case the command to run spec_res is shown first followed by the program's output.

4.1 UMS

```
<pcooper> ./spec_res -o -c -t ums_mwpc -r keat; ./spec_res -c -t ums_mwpc
#ums_mwpc       0     0 fill anal v01.00 24-Mar-2001 12:00 psc ! UMS parameters

name         material        z     phi      hz      xl     res  ptkick
ums_1x       mwpc      -1151.0      0.     0.3  .00089  .0115   0.
ums_1u       mwpc      -1150.0     60.     0.3  .00033  .0115   0.
ums_1v       mwpc      -1149.0    -60.     0.3  .00089  .0115   0.
he_bag_1     helium    -1050.0      0.    99.0  .00056  .0      0.
ums_2x       mwpc       -951.0     15.     0.3  .00089  .0115   0.
ums_2u       mwpc       -950.0     75.     0.3  .00033  .0115   0.
ums_2v       mwpc       -949.0    -45.     0.3  .00089  .0115   0.
he_bag_2     helium     -850.0      0.    99.0  .00056  .0      0.
ums_3x       mwpc       -751.0    -15.     0.3  .00089  .0115   0.
ums_3u       mwpc       -750.0     75.     0.3  .00033  .0115   0.
ums_3v       mwpc       -749.0    -45.     0.3  .00089  .0115   0.
bm109        helium     -600.0      0.   142.5  .00072  .0      0.750
ums_4x       mwpc       -451.0      0.     0.3  .00089  .0115   0.
ums_4u       mwpc       -450.0     60.     0.3  .00033  .0115   0.
ums_4v       mwpc       -449.0    -60.     0.3  .00089  .0115   0.
he_bag_4     helium     -350.0      0.    99.0  .00056  .0      0.
ums_5x       mwpc       -251.0     15.     0.3  .00089  .0115   0.
ums_5u       mwpc       -250.0     75.     0.3  .00033  .0115   0.
ums_5v       mwpc       -249.0    -45.     0.3  .00089  .0115   0.
he_bag_5     helium     -150.0      0.    99.0  .00056  .0      0.
ums_6x       mwpc        -51.0    -15.     0.3  .00089  .0115   0.
ums_6u       mwpc        -50.0     45.     0.3  .00033  .0115   0.
ums_6v       mwpc        -49.0    -75.     0.3  .00089  .0115   0.
krich_wind   steel         0.0      0.    0.05  .0050   .0      0.
krich_gas    neon        500.0      0.   500.0  .0310   .0      0.
krich_mirrorglass        998.0      0.     0.5  .0080   .0      0.
krich_wind   steel      1000.0      0.    0.05  .0050   .0      0.
keat_1x*     mwpc       1179.0      0.     0.3  .00089  .0115   0.
keat_1u*     mwpc       1180.0     60.     0.3  .00033  .0115   0.
keat_1v*     mwpc       1181.0    -60.     0.3  .00089  .0115   0.
he_bag_6     helium     1320.0      0.   159.0  .00090  .0      0.
keat_2x*     mwpc       1499.0      0.     0.3  .00089  .0115   0.
```

```
keat_2u*    mwpc      1500.0     60.     0.3  .00033  .0115   0.
keat_2v*    mwpc      1501.0    -60.     0.3  .0089  .0115   0.

spec_res -o -c -t ums_mwpc -r keat                   ! without the KEAT
  planes     sx     stx       sy     sty     sp/p
            [um]  [mRad]     [um]  [mRad]     [%]
   3FFFF   1109.   0.998   0.016   0.014  -0.428
                   0.037   0.016   0.013  -0.441
                           1004.   0.998  -0.021
                                   0.033  -0.019
                                           0.175

spec_res -c -t ums_mwpc                               ! with the KEAT
  planes     sx     stx       sy     sty     sp/p
            [um]  [mRad]     [um]  [mRad]     [%]
  FFFFFF   1096.   0.998   0.015   0.013  -0.405
                   0.036   0.014   0.012  -0.418
                           1003.   0.998  -0.019
                                   0.033  -0.017
                                           0.168

                                                      ! as a function of P

fnppd:spec_res> (./spec_res -h -L -t ums_mwpc -p 20.;
                 ./spec_res    -L -t ums_mwpc -p 21.;
                 ./spec_res    -L -t ums_mwpc -p 22.;
                 ./spec_res    -L -t ums_mwpc -p 23.;
                 ./spec_res    -L -t ums_mwpc -p 24.)

  planes    sx      stx     sy      sty     sp/p      p       z
           [um]   [mRad]   [um]   [mRad]     [%]  [GeV/c]   [cm]
  FFFFFF   1160.   0.038   1084.   0.036   0.160    20.0   2000.
  FFFFFF   1126.   0.037   1042.   0.034   0.164    21.0   2000.
  FFFFFF   1096.   0.036   1003.   0.033   0.168    22.0   2000.
  FFFFFF   1068.   0.035    968.   0.032   0.172    23.0   2000.
  FFFFFF   1043.   0.035    935.   0.031   0.175    24.0   2000.


4.2  KEAT

fnppd:spec_res> ./spec_res  -o -c -t keat_mwpc
#keat_mwpc     0     0 fill anal v01.00 23-Mar-2001 23:00 psc ! KEAT parameters

name        material        z     phi      hz      xl      res  ptkick
keat_1x     mwpc      1179.0      0.     0.3  .00089  .0115   0.
keat_1u     mwpc      1180.0     60.     0.3  .00033  .0115   0.
keat_1v     mwpc      1181.0    -60.     0.3  .00089  .0115   0.
he_bag_6    helium    1320.0      0.   159.0  .00090  .0      0.
keat_2x     mwpc      1499.0      0.     0.3  .00089  .0115   0.
keat_2u     mwpc      1500.0     60.     0.3  .00033  .0115   0.
keat_2v     mwpc      1501.0    -60.     0.3  .00089  .0115   0.

spec_res -o -c -t keat_mwpc
  planes     sx     stx       sy     sty
            [um]  [mRad]     [um]  [mRad]
      3F    335.   0.976   0.000   0.000
                   0.047   0.000   0.000
                            335.   0.976
                                   0.047
```

```
fnppd:spec_res> (./spec_res -h -L -t keat_mwpc -p 20.;  ! as a function of P
                 ./spec_res    -L -t keat_mwpc -p 21.;
                 ./spec_res    -L -t keat_mwpc -p 22.;
                 ./spec_res    -L -t keat_mwpc -p 23.;
                 ./spec_res    -L -t keat_mwpc -p 24.)

  planes    sx      stx     sy      sty       p      z
           [um]   [mRad]   [um]   [mRad]  [GeV/c]  [cm]
      3F    345.   0.048    345.   0.048    20.0   2000.
      3F    339.   0.047    339.   0.047    21.0   2000.
      3F    335.   0.047    335.   0.047    22.0   2000.
      3F    331.   0.047    330.   0.047    23.0   2000.
      3F    327.   0.046    327.   0.046    24.0   2000.
```

4.3 DMS

```
fnppd:spec_res> ./spec_res -o -c -t dms_straw
#dms_straw     0     0 fill anal v01.00  1-Sep-2000 11:50 psc ! DMS parameters

name        material        z     phi      hz       xl     res  ptkick
dms_1x      straw     4524.0      0.    0.25  .00040   .0150   0.
dms_1xp     straw     4524.5      0.    0.25  .00040   .0150   0.
dms_1y      straw     4525.0     90.    0.25  .00040   .0150   0.
dms_1yp     straw     4525.5     90.    0.25  .00040   .0150   0.
dms_1u      straw     4526.0     45.    0.25  .00040   .0150   0.
dms_2x      straw     4923.0      0.    0.25  .00040   .0150   0.
dms_2xp     straw     4923.5      0.    0.25  .00040   .0150   0.
dms_2y      straw     4924.0     90.    0.25  .00040   .0150   0.
dms_2yp     straw     4924.5     90.    0.25  .00040   .0150   0.
dms_2u      straw     4926.0     45.    0.25  .00040   .0150   0.
dms_2up     straw     4926.5     45.    0.25  .00040   .0150   0.
dms_2v      straw     4927.0    -45.    0.25  .00040   .0150   0.
dms_2vp     straw     4927.5    -45.    0.25  .00040   .0150   0.
magnet      vacuum    5000.0      0.   100.0  .0       .0      0.100
dms_3x      straw     5123.0      0.    0.25  .00040   .0150   0.
dms_3xp     straw     5123.5      0.    0.25  .00040   .0150   0.
dms_3y      straw     5124.0     90.    0.25  .00040   .0150   0.
dms_3yp     straw     5124.5     90.    0.25  .00040   .0150   0.
dms_3u      straw     5126.0     45.    0.25  .00040   .0150   0.
dms_3up     straw     5126.5     45.    0.25  .00040   .0150   0.
dms_3v      straw     5127.0    -45.    0.25  .00040   .0150   0.
dms_3vp     straw     5127.5    -45.    0.25  .00040   .0150   0.
dms_4x      straw     5523.0      0.    0.25  .00040   .0150   0.
dms_4xp     straw     5523.5      0.    0.25  .00040   .0150   0.
dms_4y      straw     5524.0     90.    0.25  .00040   .0150   0.
dms_4yp     straw     5524.5     90.    0.25  .00040   .0150   0.
dms_4u      straw     5526.0     45.    0.25  .00040   .0150   0.
dms_4up     straw     5526.5     45.    0.25  .00040   .0150   0.
dms_4v      straw     5527.0    -45.    0.25  .00040   .0150   0.
dms_4vp     straw     5527.5    -45.    0.25  .00040   .0150   0.

spec_res -o -c -t dms_straw
  planes      sx     stx       sy     sty     sp/p
            [um]  [mRad]     [um]  [mRad]      [%]
1FFFFFFF    898.  -0.997  -0.082   0.073   0.568
                   0.033   0.076  -0.067  -0.560
                            741.  -0.996  -0.052
```

```
                                         0.027   0.046
                                                 1.169


fnppd:spec_res> (./spec_res -h -L -t dms_straw -p 12.;  ! as a function of P
                 ./spec_res    -L -t dms_straw -p 13.;
                 ./spec_res    -L -t dms_straw -p 14.;
                 ./spec_res    -L -t dms_straw -p 15.;
                 ./spec_res    -L -t dms_straw -p 16.;
                 ./spec_res    -L -t dms_straw -p 17.;
                 ./spec_res    -L -t dms_straw -p 18.;
                 ./spec_res    -L -t dms_straw -p 19.;
                 ./spec_res    -L -t dms_straw -p 20.;
                 ./spec_res    -L -t dms_straw -p 21.;
                 ./spec_res    -L -t dms_straw -p 22.)

  planes    sx      stx      sy      sty     sp/p      p      z
           [um]   [mRad]   [um]   [mRad]     [%]  [GeV/c]  [cm]
1FFFFFFF   1181.   0.045   1120.   0.043   0.899    12.0   2000.
1FFFFFFF   1128.   0.043   1056.   0.040   0.922    13.0   2000.
1FFFFFFF   1083.   0.041   1002.   0.038   0.946    14.0   2000.
1FFFFFFF   1046.   0.039    955.   0.036   0.971    15.0   2000.
1FFFFFFF   1015.   0.038    914.   0.034   0.997    16.0   2000.
1FFFFFFF    988.   0.037    877.   0.033   1.023    17.0   2000.
1FFFFFFF    965.   0.036    844.   0.031   1.051    18.0   2000.
1FFFFFFF    945.   0.035    815.   0.030   1.079    19.0   2000.
1FFFFFFF    927.   0.034    788.   0.029   1.109    20.0   2000.
1FFFFFFF    912.   0.033    763.   0.028   1.138    21.0   2000.
1FFFFFFF    898.   0.033    741.   0.027   1.169    22.0   2000.


Appendix 1. man pages

SPEC_RES(1)                                                      SPEC_RES(1)



NAME
     spec_res - spectrometer resolutions including multiple Coulomb scattering

SYNOPSIS
     spec_res <-c  command line output     [none]>
              <-f  geometry file           [spec_par.ocs]>
              <-h  header output           [none]>
              <-l  single line output      [none]>
              <-L  short  line output      [none]>
              <-m  matrix output <cde>     [none]>
              <-r  remove plane from fit   [none]>
              <-o  geometry output         [none]>
              <-p  particle momentum       [22. GeV/c]>
              <-t  geometry table          [first one]>
              <-z  z origin                [2000.]>

DESCRIPTION

     spec_res calculates the complete error matrix for a tracking spectrometer
     composed of elements which can be one dimensional (projective) tracking
     planes, passive multiple scatterers and up to one magnet.
```

```
The spectrometer is described as a table in the geometry text file kept
in Selex "OCS" format.  Unlike true OCS which is free format these lines
are read in fixed columns which are:

     name      a12   element name
     material  a8    material name (unused by code)
     z         f8.0  z position of center [cm]
     phi       f8.0  azimuthal rotation for measuring plane [degrees]
     hz        f8.0  half thickness in z [cm]
     xl        f8.0  thickness in radiation lengths
     res       f8.0  resolution for measuring plane [cm] 0.==> passive
     ptkick    f8.0  Pt kick in X direction (!=0. defines the magnet)

Various input parameters (planes to remove from the fit, particle
momentum, etc.) can be changed with command line switches.

The default output is an error  matrix written to stdout with a
representation for the fit error matrix in terms of sqrt of diagonal terms
scaled into useful units ([um], [mRad] and sigma_p/p in [%]). and linear
correlation coefficients for the non-diagonal terms.  Additional outputs
are controlled with command line switches.

The fit includes 5 parameters {X[cm], Tx[Rad], Y[cm], Ty[Rad],
C=q/P}. The Tx kink angle at the magnet bend plane (C) is dropped  if the
fit region does not include a magnet.  The fit region is bounded in
Z (the beam direction) by the minimum of the Z origin, where the matrices
are evaluated and Z of the first measurement and the maximum of the Z
origin and the last measurement.

The calculation are analytic and linear.  Full Gaussian multiple Coulomb
scattering (MCS) is included.  The technique involves calculating the full
covariance matrix of all measurements.  The measurements are correlated
due to MCS in upstream measurement and passive elements creating off
diagonal terms in the covariance matrix.  The diagonal terms include
the measurement precision as in a usual linear fit.  Since the MCS scales
as 1/P while the measurement resolution is fixed for a given spectrometer
all resolutions and correlations become a function of P.  Note that the
correlation matrix is large; 28 x 28 for 28 measurements.  Double
precision is used.

Command line options are:

-c             Write out the command line
-f  file       Change geometry file read from the default [spec_par.ocs]
-h             Write out a header with variable labels and units for
               one line output (-l)
-l             Write a one line output instead of the default error matrix.
               This is the same data on a single line to allow the
               compilation of tables for various cases.  A labeled header
               for this output format is available (see -h).
-L             Write a short one line output instead of the default error
               matrix. The correlation coefficients are suppressed and the
               momentum and z origin are output.  A labeled header for this
               output format is available (see -h).
-m  <cde>      Write out selected matrices.  The 'c' matrix is the full
               inverted measurement correlation matrix.  'd' contains the
               parameter-measurement derivatives (e.g. d(2,8) is the change
               in Tx (parameter 2) for a unit change in measurement 8)
               'e' is the full 4x4 or 5x5 parameter error matrix which is
```

```
                    reformatted in the default output.
    -r  'elem'      Remove an element.  If the string 'elem' matches the name
                    of a measuring plane that measurement is removed from the
                    fit.  It remains as a passive source of MCS.  If the string
                    'elem' matches the name of a passive source of MCS its
                    radiation length is set to 0 suppressing it as a source of
                    MCS.  There can be multiple -r switches which "wild-card"
                    (e.g. -r ums -r h removes any element which has either "ums"
                    or "h" in its name).  Removed elements have a * appended to
                    their names in the -o output.
    -o              Write out the geometry table used.
    -p   mom        Change the particle momentum from the default of 22. [GeV/c].
    -t   'table'    Change the geometry table used from the default which is the
                    first one found in the geometry file.
    -z   z_org      Change the z origin (the location in the spectrometer where
                    the errors are evaluated from the default of 2000. [cm].

EXAMPLE
 spec_res -c -o -t keat_mwpc -z 1500.
#keat_mwpc     0     0 fill anal v01.00 23-Mar-2001 23:00 psc ! KEAT parameters

name        material        z     phi      hz      xl     res  ptkick
keat_1x     mwpc       1179.0      0.     0.3  .00089  .0115   0.
keat_1u     mwpc       1180.0     60.     0.3  .00033  .0115   0.
keat_1v     mwpc       1181.0    -60.     0.3  .00089  .0115   0.
he_bag_6    helium     1320.0      0.   159.0  .00090  .0      0.
keat_2x     mwpc       1499.0      0.     0.3  .00089  .0115   0.
keat_2u     mwpc       1500.0     60.     0.3  .00033  .0115   0.
keat_2v     mwpc       1501.0    -60.     0.3  .00089  .0115   0.

spec_res -c -o -h -t keat_mwpc -z 1500.
  planes      sx     stx       sy     sty
            [um]  [mRad]     [um]  [mRad]
      3F    118.   0.781   0.001   0.001
                   0.047   0.001   0.000
                            117.   0.780
                                   0.047

SEE ALSO
    The user's guide is CKM_45 in ckm notes on the web site
      http://www.fnal.gov/projects/ckm/documentation/public/CKM_45.txt
    The algorithm is documented in the Selex(E781) memo "Multiple Coulomb
    Scattering in Silicon Tracking - Addendum", Peter S. Cooper,
    February 27,1994 which can be found on the web at:
      http://fn781a.fnal.gov/~pcooper/SVX_MS_memo.ps.gz

DIAGNOSTICS
    Exit status is 0 for normal completion, 1 errors are detected.

BUGS
    None known (yet).

AUTHOR
    Peter S. Cooper  Fermi National Accelerator Laboratory  Sept  1, 2000
    revision_2 Linux version, new output formats and labels April 1, 2001
```