Supporting information for "Full vector low-temperature magnetic measurements of geologic materials"

September 17, 2014

Contents

1 Introduction

This IPython notebook contains data analysis associated with the paper:

Full vector low-temperature magnetic measurements of geologic materials

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This notebook is part of the paper's supporting online materials and is available at https://github.com/Swanson-Hysell/2014_Feinberg-et-al_LowT along with the necessary files to execute the code. Within this github repository are the following folders:

1. Code This folder contains this notebook file as well as necessary non-standard function libraries.
2. Data This folder contains the data generated for the case studies presented in this work that are used in the data analysis and presented in the paper.
3. Manuscript This folder contains the paper text and figures.

If you are viewing this supporting material as a PDF document and want to run the code in the notebook you will need to download the code from the Github repository and you will also need a Python distribution that includes IPython and the other standard scientific python libraries. There are good instructions for installing IPython/jupyter here: http://ipython.org/install.html. Alternatively you can view the notebook online with the jupyter nbviewer at this link:

Within this notebook there are data from runs on a variety of types of specimens:

- **Magnetite**: isothermal remanent magnetizations applied to a single magnetite crystal
- **Hematite**: isothermal remanent magnetization applied to a strongly foliated polycrystalline hematite sample
- **Hematite/Magnetite**: isothermal remanent magnetization applied to a Nature Company polycrystalline sample comprised of hematite and trace magnetite
- **Pyrrhotite**: isothermal remanent magnetization applied to a a single crystal of pyrrhotite
- **Coarse-grained diabase**: natural and anhysteric remanent magnetizations for samples collected from the coarse grained interior of sills from the Umkondo Large Igneous Province of Botswana

2 Import needed libraries into notebook environment

The numpy, scipy, matplotlib and pandas libraries are standard libraries for scientific python (see http://www.scipy.org). The pmag and pmagplotlib libraries are part of the PmagPy project and can be obtained from that project's github repository (https://github.com/ltauxe/PmagPy). The check_updates and get_version functions of the PmagPy libraries cause errors in the interactive environment of IPython so the code below uses a slightly modified version of those libraries that is included in the Github repository for this work. There are other functions that are necessary for the interactive plotting of paleomagnetic data (some of them edited from PmagPy) that are within the IPmag.py (see https://github.com/Swanson-Hysell/PmagPy_IPython) library that is imported in the code block below.

```
In [1]: import pmag, pmagplotlib, IPmag
        import numpy as np
        from scipy import interpolate
        import pandas as pd
        from IPython.display import display, Image, display_svg, SVG
        import matplotlib.pyplot as plt
        %matplotlib inline
```

2.1 Background substraction function

As discussed in the main text and figures, subtracting the magnetization of the blank probe is a necessary aspect of the data analysis. In order to do so, let's define a function called background_subtraction() that we can use to subtract data of a blank probe run (without a loaded sample) from data experimental runs on specimens. This function uses a spline fit to the background holder data in order to interpolate data to the temperatures where measurements were taking during the sample runs. Examples of fits to background data and subsequent background subtraction are given later in this notebook.

```
In [2]: def background_sub(background_moment, background_temp,
                           measurement_moment, measurement_temp):
            """
            subtract out data from a blank run from measurement data from a sample

            This function takes data measured with the holder alone and subtracts
            it from sample measurement data by interpolating that blank run at the
            temperatures for which data were
            """
            x = background_temp
            y = background_moment
            spline = interpolate.splrep(x,y,s=0)
            xnew = measurement_temp
            background_moment_interpolated = interpolate.splev(xnew,spline,der=0)
            bsub_moment = measurement_moment - background_moment_interpolated
            return bsub_moment
```

3 Polycrystalline hematite experiments

A polycrystalline hematite sample "Labrador hematite" was pulsed with a 1.2 T field to impart an isothermal remanent magentization (IRM) along the z axis which was then cycled from room temperature to ~130 K and back using the Institute for Rock Magnetism low temperature probe (IRM-LTI) in a superconducting rock magnetometer to collect full vector data. A low-temperature cycling experiment was also conducted using a Magnetic Properties Measurement System (MPMS) to collect 1-axis data.

3.1 IRM-LTI experiment

The data from the IRM-LTI experiment (cooling and warming data separately) can be loaded into a dataframe with the first 5 rows of the dataframe displayed.

```
In [3]: Labr_hem_cooling = pd.read_csv('../Data/Labr_hematite/Labr_hem_cooling.csv')
        Labr_hem_warming = pd.read_csv('../Data/Labr_hematite/Labr_hem_warming.csv')
        Labr_hem_warming.head()
```

```
Out[3]:                  specimen       Mx[Am2]       My[Am2]  Mz[Am2]  MN[Am2]  \
        0  Labrador hematite 02a -7.398300e-08 -1.075430e-08       -0       -0
        1  Labrador hematite 02a -7.496650e-08 -2.935900e-09       -0       -0
        2  Labrador hematite 02a -7.558250e-08 -1.850900e-09       -0       -0
        3  Labrador hematite 02a -7.607250e-08 -1.196550e-09       -0       -0
        4  Labrador hematite 02a -8.034000e-08 -2.277900e-09       -0       -0

                ME[Am2]       MV[Am2]  Mtot[Am2]  Dec[deg]  Inc[deg]    ...      \
        0 -1.075430e-08  7.398300e-08   0.000000   181.371   9.34415    ...
        1 -2.935900e-09  7.496650e-08   0.000000   180.373   9.44262    ...
        2 -1.850900e-09  7.558250e-08   0.000000   180.238   9.62523    ...
        3 -1.196550e-09  7.607250e-08   0.000000   180.155   9.77792    ...
        4 -2.277900e-09  8.034000e-08   0.000001   180.264   9.23522    ...

                  time   series  position[cm]  Drift_ratio  Ja/Jr  run#  Description  \
```

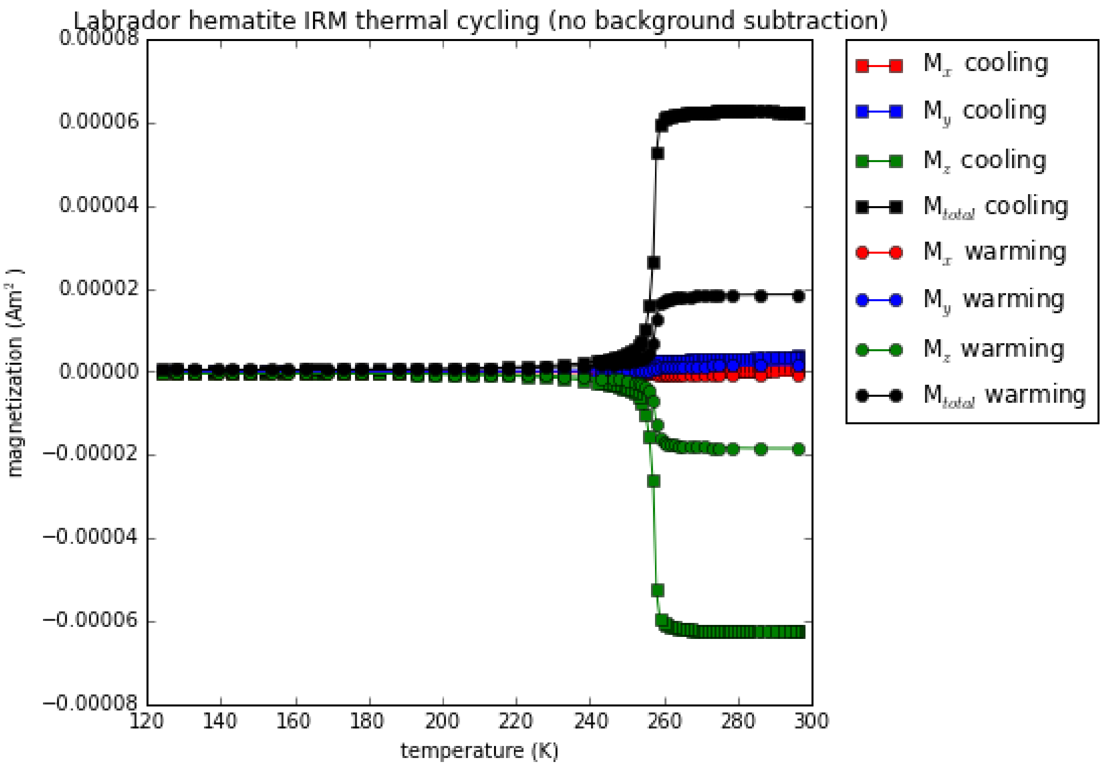
```
0  1:25:55 PM       1           NaN          NaN      0   NaN           NaN
1  1:33:42 PM       1           NaN          NaN      0   NaN           NaN
2  1:42:26 PM       1           NaN          NaN      0   NaN           NaN
3  1:48:29 PM       1           NaN          NaN      0   NaN           NaN
4  1:55:15 PM       1           NaN          NaN      0   NaN           NaN

   Meas_T[K]      Mode  Type
0        128  DISCRETE   NaN
1        133  DISCRETE   NaN
2        139  DISCRETE   NaN
3        143  DISCRETE   NaN
4        148  DISCRETE   NaN

[5 rows x 35 columns]
```

During the warming portion of the experiment one of the data points was collected during a flux jump on the SRM that was noted by the analyzer at the time and therefore has 'flux jump' in the 'Description' column. This point should be removed from the dataframe.

```
In [4]: Labr_hem_warming = Labr_hem_warming[Labr_hem_warming['Description'] != 'flux jump']
        Labr_hem_warming.reset_index(inplace=True)
```

The M_x, M_y, M_z, M_{total} values can be plotted as a function of temperature for this experiment showing the pronounced loss of remenance associated with cooling through hematite's Morin transition.

```
In [5]: plt.figure(figsize=(6,6),dpi=160)
        plt.plot(Labr_hem_cooling['Meas_T[K]'], Labr_hem_cooling['Mx[Am2]'],
                 'rs-',label='M$_x$ cooling')
        plt.plot(Labr_hem_cooling['Meas_T[K]'], Labr_hem_cooling['My[Am2]'],
                 'bs-',label='M$_y$ cooling')
        plt.plot(Labr_hem_cooling['Meas_T[K]'], Labr_hem_cooling['Mz[Am2]'],
                 'gs-',label='M$_z$ cooling')
        plt.plot(Labr_hem_cooling['Meas_T[K]'], Labr_hem_cooling['Mtot[Am2]'],
                 'ks-',label='M$_{total}$ cooling')
        plt.plot(Labr_hem_warming['Meas_T[K]'], Labr_hem_warming['Mx[Am2]'],
                 'ro-',label='M$_x$ warming')
        plt.plot(Labr_hem_warming['Meas_T[K]'], Labr_hem_warming['My[Am2]'],
                 'bo-',label='M$_y$ warming')
        plt.plot(Labr_hem_warming['Meas_T[K]'], Labr_hem_warming['Mz[Am2]'],
                 'go-',label='M$_z$ warming')
        plt.plot(Labr_hem_warming['Meas_T[K]'], Labr_hem_warming['Mtot[Am2]'],
                 'ko-',label='M$_{total}$ warming')
        plt.legend(bbox_to_anchor=(1.05, 1), loc=2, borderaxespad=0.)
        plt.xlabel('temperature (K)')
        plt.ylabel('magnetization (Am$^2$)')
        plt.title('Labrador hematite IRM thermal cycling (no background subtraction)')
        plt.show()
```

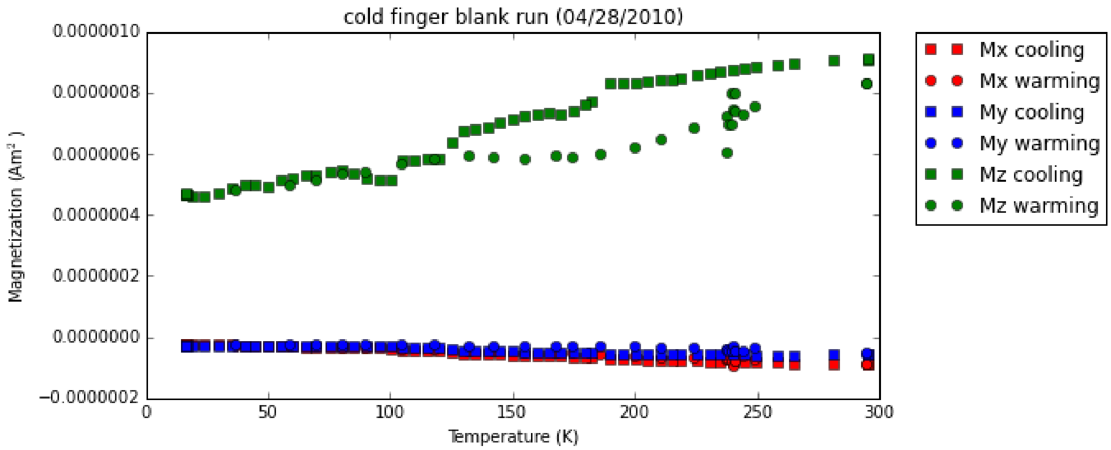


3.1.1 Background subtraction

These data need to have the background subtracted from them. We will use a run of the blank probe without a loaded sample that was conducted on 04/28/2010. Data from that blank run is imported into dataframes and plotted below.

In [6]:
```
blank_hem_data_cooling = pd.read_csv('../Data/Labr_hematite/20100428_blank_cooling.csv')
blank_hem_data_warming = pd.read_csv('../Data/Labr_hematite/20100428_blank_warming.csv')

fignum=1
plt.figure(num=fignum,figsize=(8,4),dpi=160)
plt.plot(blank_hem_data_cooling['Meas_T[K]'], blank_hem_data_cooling['Mx[Am2]'], 'rs',
         label='Mx cooling')
plt.plot(blank_hem_data_warming['Meas_T[K]'], blank_hem_data_warming['Mx[Am2]'], 'ro',
         label='Mx warming')
plt.plot(blank_hem_data_cooling['Meas_T[K]'], blank_hem_data_cooling['My[Am2]'], 'bs',
         label='My cooling')
plt.plot(blank_hem_data_warming['Meas_T[K]'], blank_hem_data_warming['My[Am2]'], 'bo',
         label='My warming')
plt.plot(blank_hem_data_cooling['Meas_T[K]'], blank_hem_data_cooling['Mz[Am2]'], 'gs',
         label='Mz cooling')
plt.plot(blank_hem_data_warming['Meas_T[K]'], blank_hem_data_warming['Mz[Am2]'], 'go',
         label='Mz warming')

plt.ylabel('Magnetization (Am$^2$)')
plt.xlabel('Temperature (K)')
```

```
plt.legend(bbox_to_anchor=(1.05, 1), loc=2, borderaxespad=0.)
plt.title('cold finger blank run (04/28/2010)')
plt.show()
```



The background_subtraction() function can be used to subtract the interpolation of data from this cold finger blank run from the measured data during the low-temperature cycling experiment on the hematite. Given that the magnetization of the cold finger looks to be more or less reversible with temperature and that there is better resolution (without a gap between 250 and 300 K) for the cooling curve, the cooling curve will be used for the background subtraction.

```
In [7]: #For the interpolate function within the background_subtraction function to
        #work, the x values (temperature) need to be sorted to be ascending.
        blank_hem_data_cooling = blank_hem_data_cooling.sort(['Meas_T[K]'])

        Mx_cooling_bsub = background_sub(blank_hem_data_cooling['Mx[Am2]'],
                                         blank_hem_data_cooling['Meas_T[K]'],
                                         Labr_hem_cooling['Mx[Am2]'],
                                         Labr_hem_cooling['Meas_T[K]'])

        My_cooling_bsub = background_sub(blank_hem_data_cooling['My[Am2]'],
                                         blank_hem_data_cooling['Meas_T[K]'],
                                         Labr_hem_cooling['My[Am2]'],
                                         Labr_hem_cooling['Meas_T[K]'])

        Mz_cooling_bsub = background_sub(blank_hem_data_cooling['Mz[Am2]'],
                                         blank_hem_data_cooling['Meas_T[K]'],
                                         Labr_hem_cooling['Mz[Am2]'],
                                         Labr_hem_cooling['Meas_T[K]'])

        Mx_warming_bsub = background_sub(blank_hem_data_cooling['Mx[Am2]'],
                                         blank_hem_data_cooling['Meas_T[K]'],
                                         Labr_hem_warming['Mx[Am2]'],
                                         Labr_hem_warming['Meas_T[K]'])

        My_warming_bsub = background_sub(blank_hem_data_cooling['My[Am2]'],
                                         blank_hem_data_cooling['Meas_T[K]'],
                                         Labr_hem_warming['My[Am2]'],
```

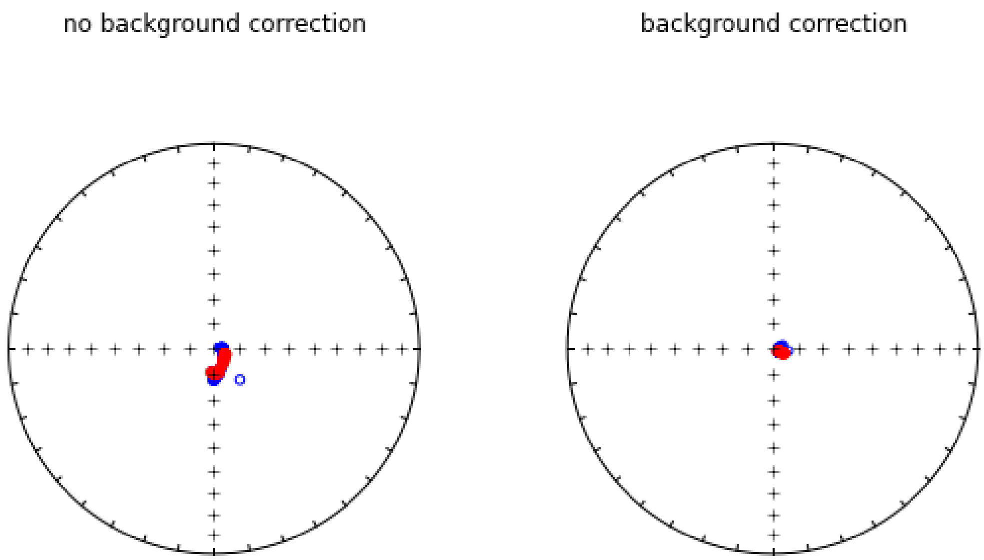
```
                                  Labr_hem_warming['Meas_T[K]'])

Mz_warming_bsub = background_sub(blank_hem_data_cooling['Mz[Am2]'],
                                  blank_hem_data_cooling['Meas_T[K]'],
                                  Labr_hem_warming['Mz[Am2]'],
                                  Labr_hem_warming['Meas_T[K]'])

#calculate the full vector after background subtraction
Mtotal_cooling = np.sqrt(Mx_cooling_bsub**2+My_cooling_bsub**2+Mz_cooling_bsub**2)
Mtotal_warming = np.sqrt(Mx_warming_bsub**2+My_warming_bsub**2+Mz_warming_bsub**2)
#the specimen weighs 1.0129 g to get the units into Am2/kg let's divide by 1.0129/1000
Mtotal_cooling_mass_normalized = Mtotal_cooling/(1.0129/1000)
Mtotal_warming_mass_normalized = Mtotal_warming/(1.0129/1000)
```

3.1.2 Directional data

In addition to plotting the magnetization along each axis, the directions of the data can be plotted on an equal area plot. The code below generates a plot that shows the directions from throughout the low-temperature cycling both without background subtraction and with background subtraction.

```
In [8]: directions_cooling_cart=[]
        directions_warming_cart=[]

        for n in range(len(Labr_hem_cooling)):
            directions_cooling_cart.append([Labr_hem_cooling['Mx[Am2]'][n],
                                            Labr_hem_cooling['My[Am2]'][n],
                                            Labr_hem_cooling['Mz[Am2]'][n]])
        for n in range(len(Labr_hem_warming)):
            directions_warming_cart.append([Labr_hem_warming['Mx[Am2]'][n],
                                            Labr_hem_warming['My[Am2]'][n],
                                            Labr_hem_warming['Mz[Am2]'][n]])

        directions_cooling_DI=pmag.cart2dir(directions_cooling_cart)
        directions_warming_DI=pmag.cart2dir(directions_warming_cart)

        directions_bsub_cooling_cart=[]
        directions_bsub_warming_cart=[]

        for n in range(len(Labr_hem_cooling)):
            directions_bsub_cooling_cart.append([Mx_cooling_bsub[n],
                                                 My_cooling_bsub[n],
                                                 Mz_cooling_bsub[n]])
        for n in range(len(Labr_hem_warming)):
            directions_bsub_warming_cart.append([Mx_warming_bsub[n],
                                                 My_warming_bsub[n],
                                                 Mz_warming_bsub[n]])

        directions_bsub_cooling_DI=pmag.cart2dir(directions_bsub_cooling_cart)
        directions_bsub_warming_DI=pmag.cart2dir(directions_bsub_warming_cart)

        fig=plt.figure(figsize=(8,5),dpi=160)

        plt.subplot(121)
        pmagplotlib.plotNET(fignum)
        IPmag.iplotDI(directions_cooling_DI,'b')
```

```
IPmag.iplotDI(directions_warming_DI,'r')
plt.title('no background correction')

plt.subplot(122)
pmagplotlib.plotNET(fignum)
IPmag.iplotDI(directions_bsub_cooling_DI,'b')
IPmag.iplotDI(directions_bsub_warming_DI,'r')
plt.title('background correction')
plt.savefig('code_output/Labr_hem_eqarea.pdf')
plt.show()
```



It is clear from the above plot that the background subtraction implementation was effective in removing signal associated with the blank probe. Note that at the time of this experiment the probe was more magnetic than it is at present as there were subsequent improvements. See the main text for details.

3.2 MPMS experiment

In addition to the 3-axis data obtained with the IRM-LTI, we obtained single axis data on the hematite sample using an MPMS. These data can be imported into a data frame.

```
In [9]: Labr_hem_MPMS = pd.read_csv('../Data/Labr_hematite/Labr_hem_MPMS.csv')
        Labr_hem_MPMS.head()
```

Out[9]:

	T [K]	Bapp [T]	M [Am2/kg]	reg fit	timestamp	T [K].1 \
0	299.9905	0	0.041991	0.970553	5/7/2010 12:11:45 PM	19.99694
1	294.3364	0	0.041716	0.970341	5/7/2010 12:15:20 PM	25.49144
2	289.1934	0	0.041456	0.970064	5/7/2010 12:16:10 PM	30.56160
3	284.0423	0	0.041179	0.969775	5/7/2010 12:16:56 PM	35.57994
4	279.7256	0	0.040682	0.969927	5/7/2010 12:19:34 PM	40.53156

```
   Bapp [T].1  M [Am2/kg].1  reg fit.1   timestamp.1
0           0      0.001129   0.989705  5/7/10 15:18
1           0      0.001129   0.989654  5/7/10 15:20
2           0      0.001129   0.989615  5/7/10 15:21
3           0      0.001128   0.989613  5/7/10 15:22
4           0      0.001128   0.989653  5/7/10 15:23
```

3.3 Comparision between IRM-LTI and MPMS data

As can be seen in the output of the code cell below, the magnetization measured at ~289 K (the temperature to which the plots have been normalized) for the specimen was about 33% lower on the specimen on the MPMS than on the IRM-LTI. This could be due, in part, to a portion of the magnetization being off of the one axis being measured on the MPMS.

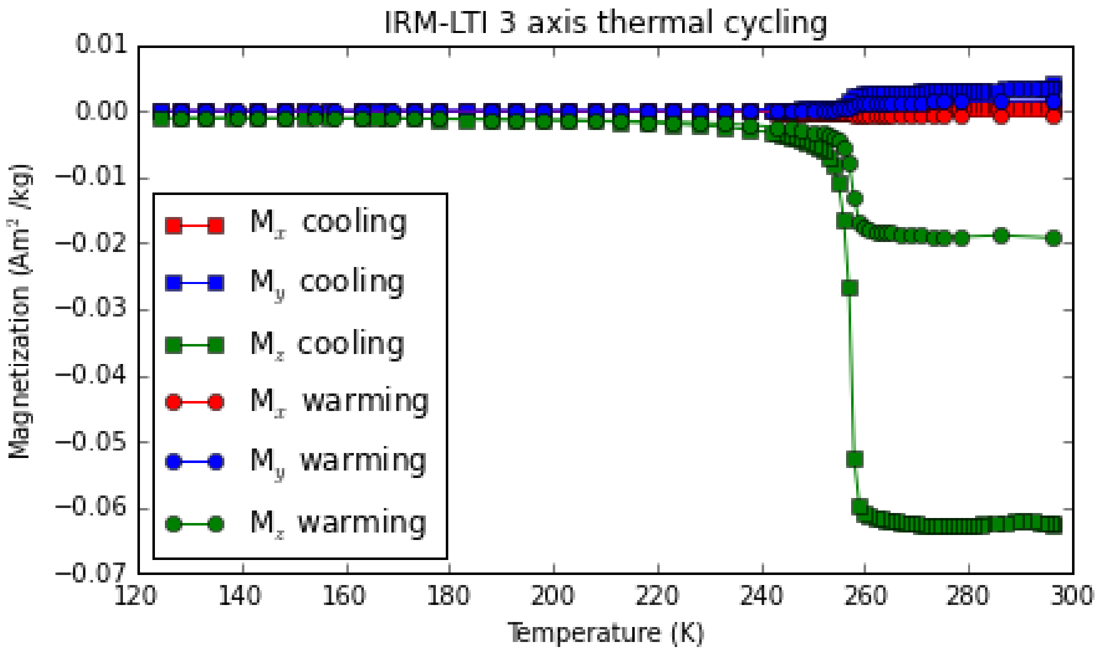
```
In [10]: Labr_hem_MPMS_289 = Labr_hem_MPMS['M [Am2/kg]'][2]
         Labr_hem_LTI_289 = Mtotal_cooling_mass_normalized[7]
         print 'At this temperature (K):'
         print Labr_hem_MPMS['T [K]'][2]
         print 'The magnetization of the hematite sample on the MPMS is (Am2/kg):'
         print Labr_hem_MPMS_289
         print ''
         print 'At this temperature (K):'
         print Labr_hem_cooling['Meas_T[K]'][7]
         print 'The magnetization of the hematite sample on the IRM-LTI is (Am2/kg):'
         print Labr_hem_LTI_289
         print ""
         print 'The percentage difference between the magnetizations is:'
         print ((Labr_hem_LTI_289-Labr_hem_MPMS_289)/Labr_hem_LTI_289)*100
```

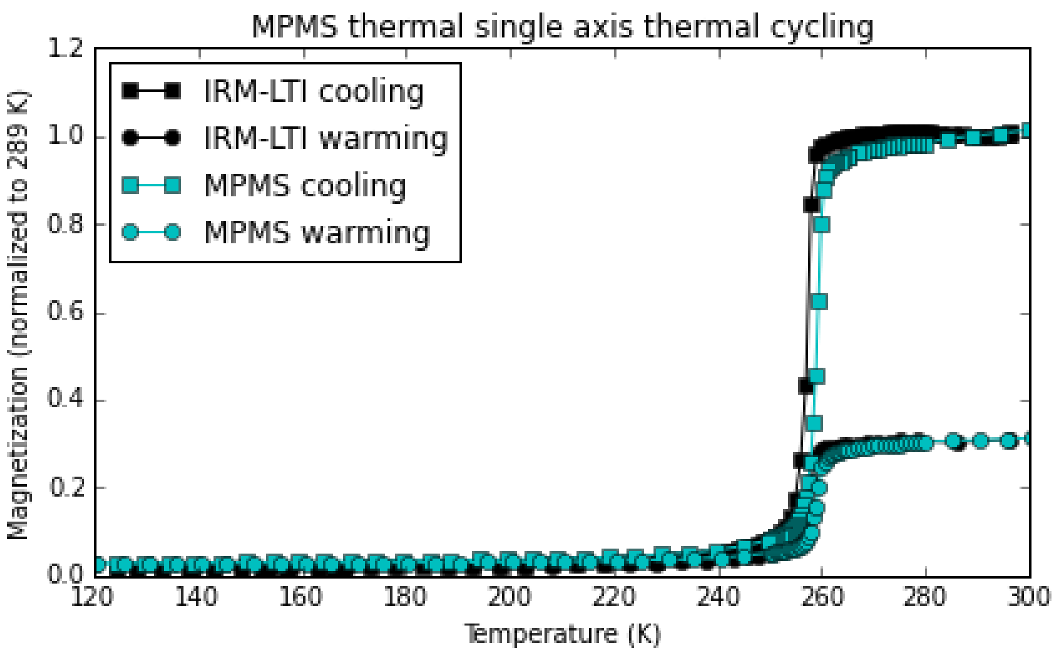
```
At this temperature (K):
289.1934
The magnetization of the hematite sample on the MPMS is (Am2/kg):
0.041456254

At this temperature (K):
289.0
The magnetization of the hematite sample on the IRM-LTI is (Am2/kg):
0.0622871852112

The percentage difference between the magnetizations is:
33.4433658232
```

Let's make a plot where the MPMS and LTI data are normalized so that they can be directly compared.

```
In [11]: adjustprops = dict(left=0.1, bottom=0.1, right=0.97, top=0.93, wspace=0.25, hspace=0.25)
         fig=plt.figure(figsize=(6,8),dpi=160)
         fig.subplots_adjust(**adjustprops)
         ax1 = plt.subplot(211)

         ax1.plot(Labr_hem_cooling['Meas_T[K]'], Mx_cooling_bsub/(1.0129/1000),
                  'rs-',label='M$_x$ cooling')
         ax1.plot(Labr_hem_cooling['Meas_T[K]'], My_cooling_bsub/(1.0129/1000),
                  'bs-',label='M$_y$ cooling')
         ax1.plot(Labr_hem_cooling['Meas_T[K]'], Mz_cooling_bsub/(1.0129/1000),
                  'gs-',label='M$_z$ cooling')
```

```
ax1.plot(Labr_hem_warming['Meas_T[K]'], Mx_warming_bsub/(1.0129/1000),
         'ro-',label='M$_x$ warming')
ax1.plot(Labr_hem_warming['Meas_T[K]'], My_warming_bsub/(1.0129/1000),
         'bo-',label='M$_y$ warming')
ax1.plot(Labr_hem_warming['Meas_T[K]'], Mz_warming_bsub/(1.0129/1000),
         'go-',label='M$_z$ warming')
plt.legend(loc=3)
plt.title('IRM-LTI 3 axis thermal cycling')
plt.xlabel('Temperature (K)')
plt.ylabel('Magnetization (Am$^2$/kg)')

ax2 = plt.subplot(212)
ax2.plot(Labr_hem_cooling['Meas_T[K]'],Mtotal_cooling_mass_normalized/Labr_hem_LTI_289,
         'ks-', label='IRM-LTI cooling')
ax2.plot(Labr_hem_warming['Meas_T[K]'],Mtotal_warming_mass_normalized/Labr_hem_LTI_289,
         'ko-', label='IRM-LTI warming')
ax2.plot(Labr_hem_MPMS['T [K]'],Labr_hem_MPMS['M [Am2/kg]']/Labr_hem_MPMS_289,
         'cs-', label='MPMS cooling')
ax2.plot(Labr_hem_MPMS['T [K].1'],Labr_hem_MPMS['M [Am2/kg].1']/Labr_hem_MPMS_289,
         'co-', label='MPMS warming')
plt.xlim(120, 300)
plt.ylim(ymin=0)
plt.title('MPMS thermal single axis thermal cycling')
plt.xlabel('Temperature (K)')
plt.ylabel('Magnetization (normalized to 289 K)')
plt.legend(loc=2)
plt.savefig('code_output/Labr_hem_data.pdf')
plt.show()
```

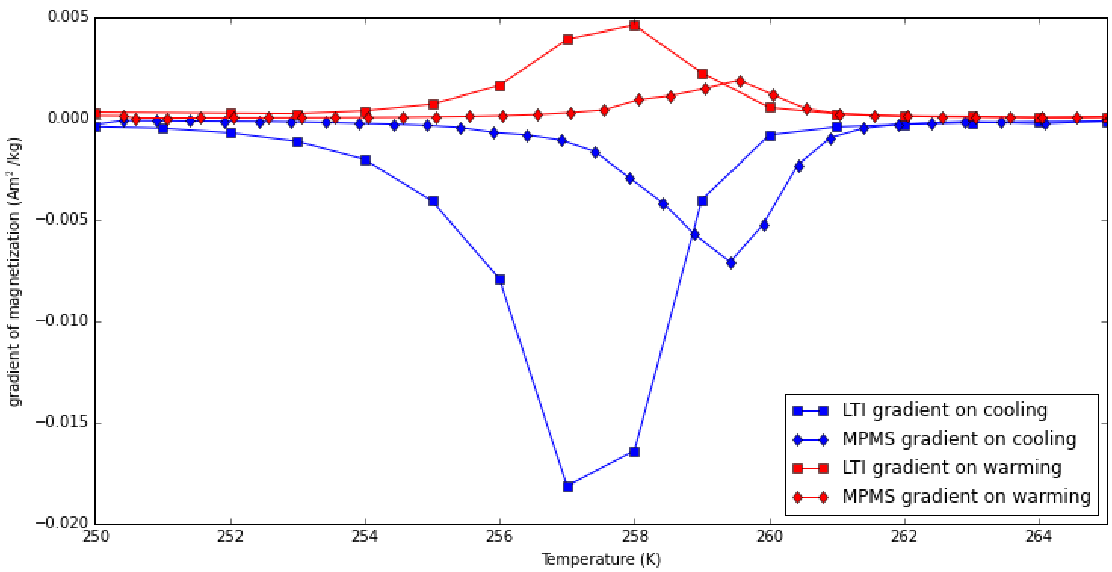




There looks to be a slight temperature difference between loss of remanence observed using the IRM-LTI and the MPMS. This difference can be see more clearly in the gradient of the low-temperature cycling data. These gradient data can then be used to make estimates of the Morin transition temperature with each method to quantify the magnitude of this temperature difference.

```
In [12]: gradient_LTI_cooling = np.gradient(Mtotal_cooling_mass_normalized)
         gradient_MPMS_cooling = np.gradient(Labr_hem_MPMS['M [Am2/kg]'][0:94])
         gradient_LTI_warming = np.gradient(Mtotal_warming_mass_normalized)
         gradient_MPMS_warming = np.gradient(Labr_hem_MPMS['M [Am2/kg].1'])
```

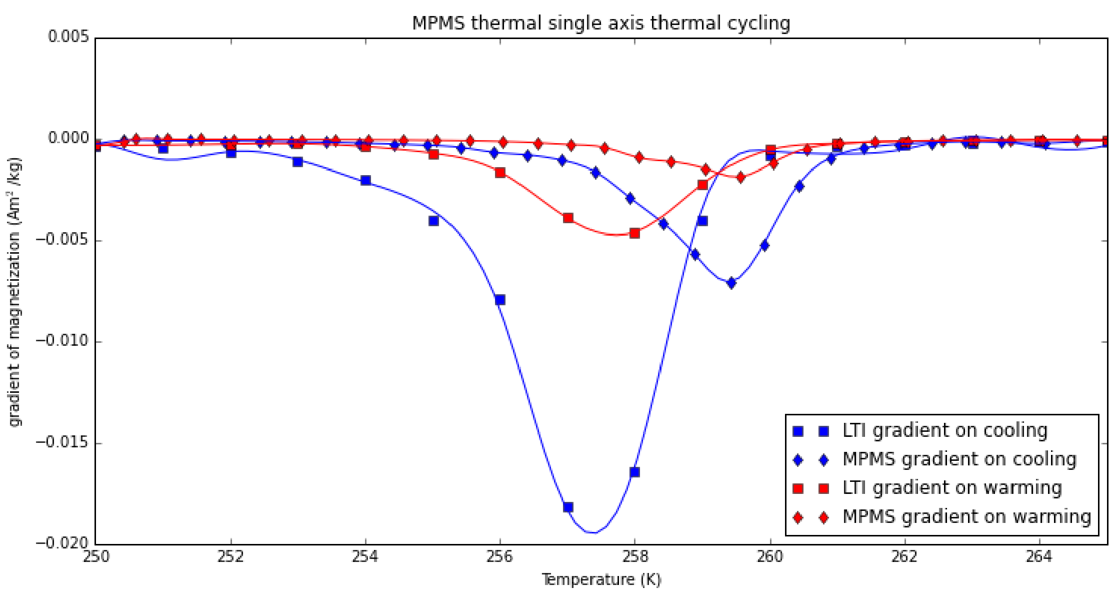
```
fig=plt.figure(figsize=(12,6),dpi=160)
plt.plot(Labr_hem_cooling['Meas_T[K]'], gradient_LTI_cooling,
         'bs-',label='LTI gradient on cooling')
plt.plot(Labr_hem_MPMS['T [K]'][0:94],gradient_MPMS_cooling,
         'bd-', label='MPMS gradient on cooling')
plt.plot(Labr_hem_warming['Meas_T[K]'], gradient_LTI_warming,
         'rs-',label='LTI gradient on warming')
plt.plot(Labr_hem_MPMS['T [K].1'],gradient_MPMS_warming,
         'rd-', label='MPMS gradient on warming')
plt.xlim(250, 265)
plt.xlabel('Temperature (K)')
plt.ylabel('gradient of magnetization (Am$^2$/kg)')
plt.legend(loc=4)
plt.show()
```



To estimate the Morin temperature using these data, let's fit cubic splines to the data. For comparision of the warming and cooling data the negative of the gradient upon warming will be calculated and plotted. The plot compares the data points themselves with the interpolated spline fit.

```
In [13]: from scipy.interpolate import interp1d

         #interpolate the data using a cubic spline
         f_LTI_cooling_inter =  interp1d(Labr_hem_cooling['Meas_T[K]'], gradient_LTI_cooling,
                                kind='cubic')
         f_MPMS_cooling_inter = interp1d(Labr_hem_MPMS['T [K]'][0:94], gradient_MPMS_cooling,
                                kind='cubic')
         f_LTI_warming_inter =  interp1d(Labr_hem_warming['Meas_T[K]'], -gradient_LTI_warming,
                                kind='cubic')
         f_MPMS_warming_inter = interp1d(Labr_hem_MPMS['T [K].1'], -gradient_MPMS_warming,
                                kind='cubic')

         xnew = np.linspace(250,265,100)

         gradient_MPMS_cooling_interpolated = f_MPMS_cooling_inter(xnew)
```

```
gradient_LTI_cooling_interpolated = f_LTI_cooling_inter(xnew)
gradient_MPMS_warming_interpolated = f_MPMS_warming_inter(xnew)
gradient_LTI_warming_interpolated = f_LTI_warming_inter(xnew)

fig=plt.figure(figsize=(12,6),dpi=160)
plt.plot(Labr_hem_cooling['Meas_T[K]'],gradient_LTI_cooling,
         'bs',label='LTI gradient on cooling')
plt.plot(Labr_hem_MPMS['T [K]'][0:94],gradient_MPMS_cooling,
         'bd', label='MPMS gradient on cooling')
plt.plot(Labr_hem_warming['Meas_T[K]'],-gradient_LTI_warming,
         'rs',label='LTI gradient on warming')
plt.plot(Labr_hem_MPMS['T [K].1'],-gradient_MPMS_warming,
         'rd', label='MPMS gradient on warming')
plt.xlim(250, 265)
plt.title('MPMS thermal single axis thermal cycling')
plt.xlabel('Temperature (K)')
plt.ylabel('gradient of magnetization (Am$^2$/kg)')
plt.legend(loc=4)

plt.plot(xnew, gradient_MPMS_cooling_interpolated, 'b-')
plt.plot(xnew, gradient_LTI_cooling_interpolated, 'b-')
plt.plot(xnew, gradient_MPMS_warming_interpolated, 'r-')
plt.plot(xnew, gradient_LTI_warming_interpolated, 'r-')
plt.show()
```



The downhill simplex algorithm as implemented in scipy.optimize can be used to find the peak of the interpolated data. This peak is the estimate of the Morin transition temperature.

```
In [14]: from scipy.optimize import fmin
         gradient_LTI_cooling_min = fmin(f_LTI_cooling_inter, x0=257)
         print 'The peak gradient for LTI cooling is at: ' + str(gradient_LTI_cooling_min)
         print ""
         gradient_MPMS_cooling_min = fmin(f_MPMS_cooling_inter, x0=259)
```

```
        print 'The peak gradient for MPMS cooling is at: ' + str(gradient_MPMS_cooling_min)
        print ""
        gradient_LTI_warming_min = fmin(f_LTI_warming_inter, x0=257)
        print 'The peak gradient for LTI warming is at: ' + str(gradient_LTI_warming_min)
        print ""
        gradient_MPMS_warming_min = fmin(f_MPMS_warming_inter, x0=259)
        print 'The peak gradient for MPMS cooling is at: ' + str(gradient_MPMS_warming_min)
```

```
Optimization terminated successfully.
         Current function value: -0.019496
         Iterations: 18
         Function evaluations: 36
The peak gradient for LTI cooling is at: [ 257.37332764]

Optimization terminated successfully.
         Current function value: -0.007081
         Iterations: 18
         Function evaluations: 37
The peak gradient for MPMS cooling is at: [ 259.39302902]

Optimization terminated successfully.
         Current function value: -0.004769
         Iterations: 18
         Function evaluations: 36
The peak gradient for LTI warming is at: [ 257.7300869]

Optimization terminated successfully.
         Current function value: -0.001900
         Iterations: 18
         Function evaluations: 37
The peak gradient for MPMS cooling is at: [ 259.51168861]
```

Given that the magnitude of the transition is greater upon cooling, we use the Morin transition temperature estimates from the cooling curves in the main text of the paper where we note that there is a 2 degree difference between the Morin transition temperature was estimated using the IRM-LTI (257.4 K) in comparision to the MPMS (259.4 K).

4 Single crystal magnetite experiments

4.1 IRM-LTI experiments

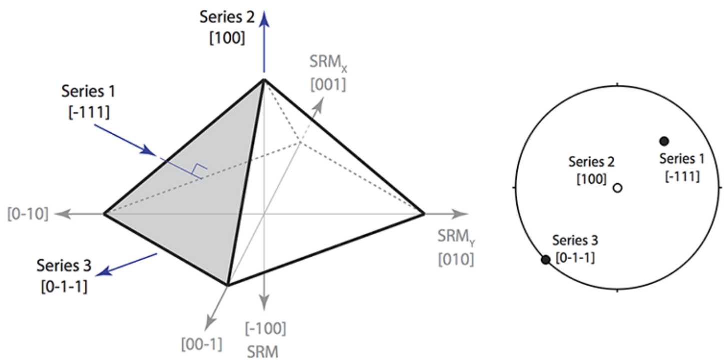
A specimen cut from single crystal magnetite octahedron (IKON magnetite) underwent a series of experiments where IRM magnetizations were applied along different axes and then cycled to low temperature using the IRM-LTI.

- Series 1 experiment was designed to apply an IRM along the $< 111 >$
- Series 2 experiment was designed to apply an IRM along the $< 100 >$ "SIRM 1.2T (350 Volt pulse) along 100 (along Z)"
- Series 3 experiment was designed to apply the magnetization along the $< 110 >$

A schematic drawing of the specimen and its orientation relative to the measurement axes of the superconducting rock magnetometer (SRM) and to the orientations of three separate 1.2 T IRMs is shown below.

```
In [15]: Image(filename=('../Data/Ikon_magnetite/experiment_schematic.png'))
```

Out[15]:



The data from these experiments can be imported into data frames.

In [16]:
```
Ikon_series1_cooling = pd.read_csv('../Data/Ikon_magnetite/Ikon_mag_series1_cooling.csv')
Ikon_series1_warming = pd.read_csv('../Data/Ikon_magnetite/Ikon_mag_series1_warming.csv')

Ikon_series2_cooling = pd.read_csv('../Data/Ikon_magnetite/Ikon_mag_series2_cooling.csv')
Ikon_series2_warming = pd.read_csv('../Data/Ikon_magnetite/Ikon_mag_series2_warming.csv')

Ikon_series3_cooling = pd.read_csv('../Data/Ikon_magnetite/Ikon_mag_series3_cooling.csv')
Ikon_series3_warming = pd.read_csv('../Data/Ikon_magnetite/Ikon_mag_series3_warming.csv')
```

The blank holder data used for the background correction of the Labrador hematite sample will also be used to the background correction for these experiments as these data were collected in the same interval of time that the instrument was in use.

In [17]:
```
#For the interpolate function to work the x values (temperature) need to be ascending.
#The blank_hem_data_cooling can be sorted so that temperatures are ascending
blank_hem_data_cooling = blank_hem_data_cooling.sort(['Meas_T[K]'])

Ikon_series1_cooling['Mx_bsub[Am2]'] = background_sub(blank_hem_data_cooling['Mx[Am2]'],
                                                      blank_hem_data_cooling['Meas_T[K]'],
                                                      Ikon_series1_cooling['Mx[Am2]'],
                                                      Ikon_series1_cooling['Meas_T[K]'])

Ikon_series1_cooling['My_bsub[Am2]'] = background_sub(blank_hem_data_cooling['My[Am2]'],
                                                      blank_hem_data_cooling['Meas_T[K]'],
                                                      Ikon_series1_cooling['My[Am2]'],
                                                      Ikon_series1_cooling['Meas_T[K]'])

Ikon_series1_cooling['Mz_bsub[Am2]'] = background_sub(blank_hem_data_cooling['Mz[Am2]'],
                                                      blank_hem_data_cooling['Meas_T[K]'],
                                                      Ikon_series1_cooling['Mz[Am2]'],
                                                      Ikon_series1_cooling['Meas_T[K]'])

Ikon_series1_warming['Mx_bsub[Am2]'] = background_sub(blank_hem_data_cooling['Mx[Am2]'],
                                                      blank_hem_data_cooling['Meas_T[K]'],
                                                      Ikon_series1_warming['Mx[Am2]'],
                                                      Ikon_series1_warming['Meas_T[K]'])
```

```
Ikon_series1_warming['My_bsub[Am2]'] = background_sub(blank_hem_data_cooling['My[Am2]'],
                                       blank_hem_data_cooling['Meas_T[K]'],
                                       Ikon_series1_warming['My[Am2]'],
                                       Ikon_series1_warming['Meas_T[K]'])

Ikon_series1_warming['Mz_bsub[Am2]'] = background_sub(blank_hem_data_cooling['Mz[Am2]'],
                                       blank_hem_data_cooling['Meas_T[K]'],
                                       Ikon_series1_warming['Mz[Am2]'],
                                       Ikon_series1_warming['Meas_T[K]'])

Ikon_series2_cooling['Mx_bsub[Am2]'] = background_sub(blank_hem_data_cooling['Mx[Am2]'],
                                       blank_hem_data_cooling['Meas_T[K]'],
                                       Ikon_series2_cooling['Mx[Am2]'],
                                       Ikon_series2_cooling['Meas_T[K]'])

Ikon_series2_cooling['My_bsub[Am2]'] = background_sub(blank_hem_data_cooling['My[Am2]'],
                                       blank_hem_data_cooling['Meas_T[K]'],
                                       Ikon_series2_cooling['My[Am2]'],
                                       Ikon_series2_cooling['Meas_T[K]'])

Ikon_series2_cooling['Mz_bsub[Am2]'] = background_sub(blank_hem_data_cooling['Mz[Am2]'],
                                       blank_hem_data_cooling['Meas_T[K]'],
                                       Ikon_series2_cooling['Mz[Am2]'],
                                       Ikon_series2_cooling['Meas_T[K]'])

Ikon_series2_warming['Mx_bsub[Am2]'] = background_sub(blank_hem_data_cooling['Mx[Am2]'],
                                       blank_hem_data_cooling['Meas_T[K]'],
                                       Ikon_series2_warming['Mx[Am2]'],
                                       Ikon_series2_warming['Meas_T[K]'])

Ikon_series2_warming['My_bsub[Am2]'] = background_sub(blank_hem_data_cooling['My[Am2]'],
                                       blank_hem_data_cooling['Meas_T[K]'],
                                       Ikon_series2_warming['My[Am2]'],
                                       Ikon_series2_warming['Meas_T[K]'])

Ikon_series2_warming['Mz_bsub[Am2]'] = background_sub(blank_hem_data_cooling['Mz[Am2]'],
                                       blank_hem_data_cooling['Meas_T[K]'],
                                       Ikon_series2_warming['Mz[Am2]'],
                                       Ikon_series2_warming['Meas_T[K]'])

Ikon_series3_cooling['Mx_bsub[Am2]'] = background_sub(blank_hem_data_cooling['Mx[Am2]'],
                                       blank_hem_data_cooling['Meas_T[K]'],
                                       Ikon_series3_cooling['Mx[Am2]'],
                                       Ikon_series3_cooling['Meas_T[K]'])

Ikon_series3_cooling['My_bsub[Am2]'] = background_sub(blank_hem_data_cooling['My[Am2]'],
                                       blank_hem_data_cooling['Meas_T[K]'],
                                       Ikon_series3_cooling['My[Am2]'],
                                       Ikon_series3_cooling['Meas_T[K]'])

Ikon_series3_cooling['Mz_bsub[Am2]'] = background_sub(blank_hem_data_cooling['Mz[Am2]'],
                                       blank_hem_data_cooling['Meas_T[K]'],
                                       Ikon_series3_cooling['Mz[Am2]'],
```

```
                                                    Ikon_series3_cooling['Meas_T[K]'])

        Ikon_series3_warming['Mx_bsub[Am2]'] = background_sub(blank_hem_data_cooling['Mx[Am2]'],
                                                              blank_hem_data_cooling['Meas_T[K]'],
                                                              Ikon_series3_warming['Mx[Am2]'],
                                                              Ikon_series3_warming['Meas_T[K]'])

        Ikon_series3_warming['My_bsub[Am2]'] = background_sub(blank_hem_data_cooling['My[Am2]'],
                                                              blank_hem_data_cooling['Meas_T[K]'],
                                                              Ikon_series3_warming['My[Am2]'],
                                                              Ikon_series3_warming['Meas_T[K]'])

        Ikon_series3_warming['Mz_bsub[Am2]'] = background_sub(blank_hem_data_cooling['Mz[Am2]'],
                                                              blank_hem_data_cooling['Meas_T[K]'],
                                                              Ikon_series3_warming['Mz[Am2]'],
                                                              Ikon_series3_warming['Meas_T[K]'])
```

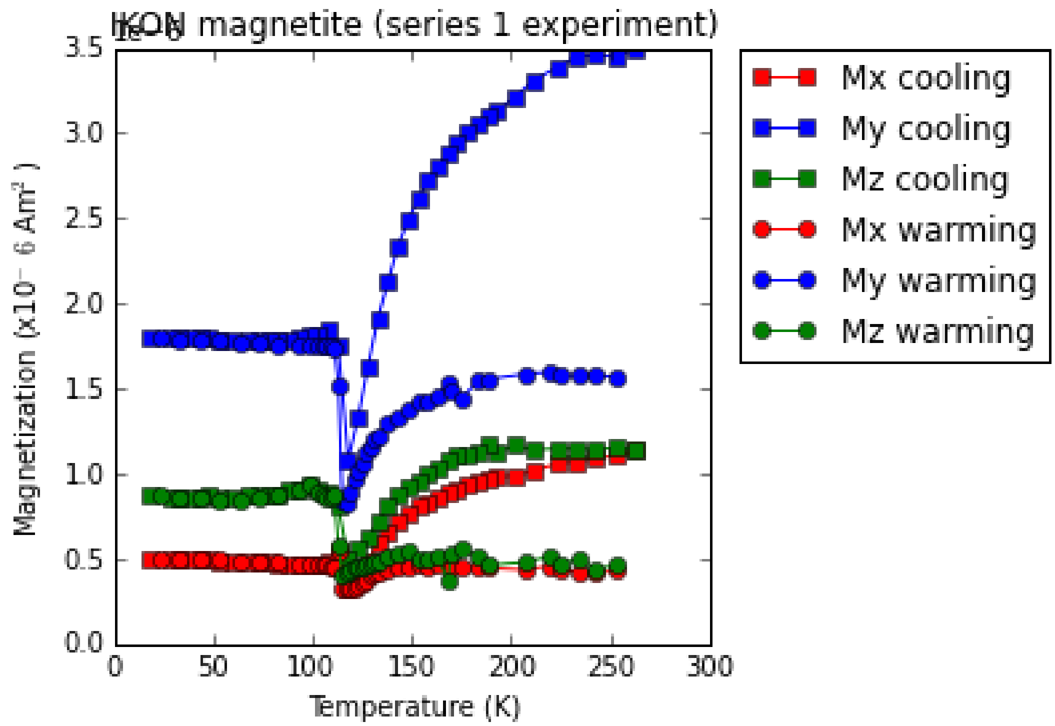
From these background corrected three-axis data the total vector can be calculated.

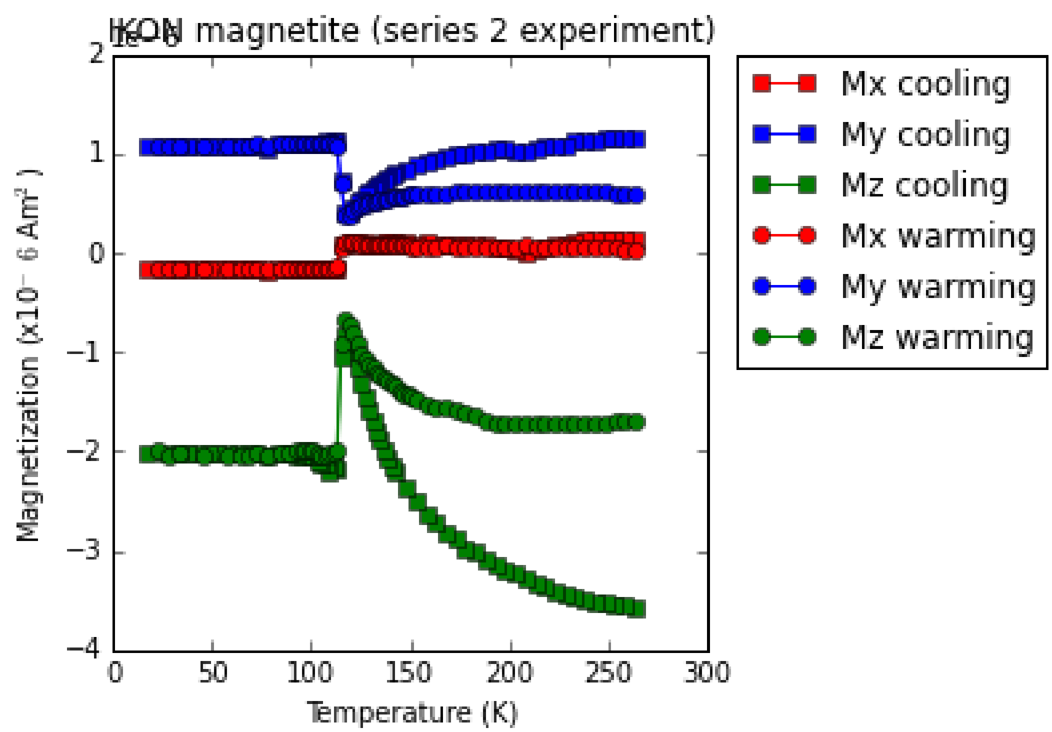
```
In [18]: Ikon_series1_cooling['Mtotal_bsub[Am2]'] = np.sqrt(Ikon_series1_cooling['Mx_bsub[Am2]']**2+
                                                           Ikon_series1_cooling['My_bsub[Am2]']**2+
                                                           Ikon_series1_cooling['Mz_bsub[Am2]']**2)
         Ikon_series1_warming['Mtotal_bsub[Am2]'] = np.sqrt(Ikon_series1_warming['Mx_bsub[Am2]']**2+
                                                           Ikon_series1_warming['My_bsub[Am2]']**2+
                                                           Ikon_series1_warming['Mz_bsub[Am2]']**2)

         Ikon_series2_cooling['Mtotal_bsub[Am2]'] = np.sqrt(Ikon_series2_cooling['Mx_bsub[Am2]']**2+
                                                           Ikon_series2_cooling['My_bsub[Am2]']**2+
                                                           Ikon_series2_cooling['Mz_bsub[Am2]']**2)
         Ikon_series2_warming['Mtotal_bsub[Am2]'] = np.sqrt(Ikon_series2_warming['Mx_bsub[Am2]']**2+
                                                           Ikon_series2_warming['My_bsub[Am2]']**2+
                                                           Ikon_series2_warming['Mz_bsub[Am2]']**2)

         Ikon_series3_cooling['Mtotal_bsub[Am2]'] = np.sqrt(Ikon_series3_cooling['Mx_bsub[Am2]']**2+
                                                           Ikon_series3_cooling['My_bsub[Am2]']**2+
                                                           Ikon_series3_cooling['Mz_bsub[Am2]']**2)
         Ikon_series3_warming['Mtotal_bsub[Am2]'] = np.sqrt(Ikon_series3_warming['Mx_bsub[Am2]']**2+
                                                           Ikon_series3_warming['My_bsub[Am2]']**2+
                                                           Ikon_series3_warming['Mz_bsub[Am2]']**2)
```

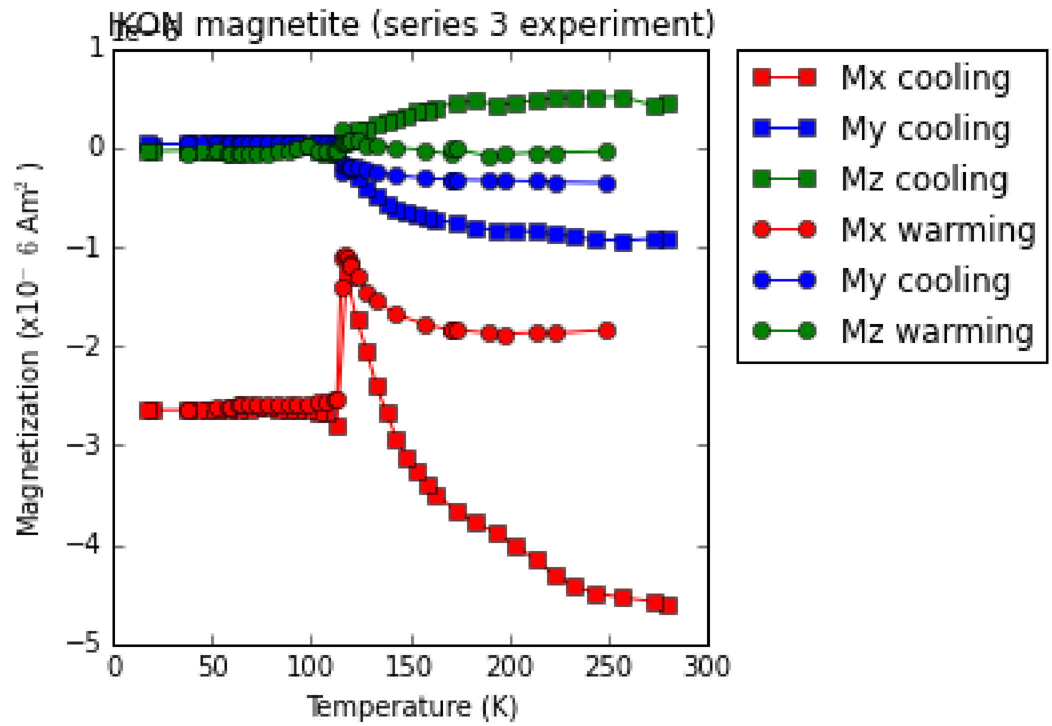
Plot the three-axis data for each experiment.

```
In [19]: plt.figure(figsize=(4,4),dpi=160)
         plt.plot(Ikon_series1_cooling['Meas_T[K]'], Ikon_series1_cooling['Mx_bsub[Am2]'], 'rs-',
                  label='Mx cooling')
         plt.plot(Ikon_series1_cooling['Meas_T[K]'], Ikon_series1_cooling['My_bsub[Am2]'], 'bs-',
                  label='My cooling')
         plt.plot(Ikon_series1_cooling['Meas_T[K]'], Ikon_series1_cooling['Mz_bsub[Am2]'], 'gs-',
                  label='Mz cooling')
         plt.plot(Ikon_series1_warming['Meas_T[K]'], Ikon_series1_warming['Mx_bsub[Am2]'], 'ro-',
                  label='Mx warming')
         plt.plot(Ikon_series1_warming['Meas_T[K]'], Ikon_series1_warming['My_bsub[Am2]'], 'bo-',
                  label='My warming')
         plt.plot(Ikon_series1_warming['Meas_T[K]'], Ikon_series1_warming['Mz_bsub[Am2]'], 'go-',
                  label='Mz warming')
```

```
plt.ylabel('Magnetization (x10$^-6$ Am$^2$)')
plt.ticklabel_format(style='sci', scilimits=(0,0), axis='y')
plt.xlabel('Temperature (K)')
plt.legend(bbox_to_anchor=(1.05, 1), loc=2, borderaxespad=0.)
plt.title('IKON magnetite (series 1 experiment)')
plt.show()

plt.figure(figsize=(4,4),dpi=160)
plt.plot(Ikon_series2_cooling['Meas_T[K]'], Ikon_series2_cooling['Mx_bsub[Am2]'], 'rs-',
         label='Mx cooling')
plt.plot(Ikon_series2_cooling['Meas_T[K]'], Ikon_series2_cooling['My_bsub[Am2]'], 'bs-',
         label='My cooling')
plt.plot(Ikon_series2_cooling['Meas_T[K]'], Ikon_series2_cooling['Mz_bsub[Am2]'], 'gs-',
         label='Mz cooling')
plt.plot(Ikon_series2_warming['Meas_T[K]'], Ikon_series2_warming['Mx_bsub[Am2]'], 'ro-',
         label='Mx warming')
plt.plot(Ikon_series2_warming['Meas_T[K]'], Ikon_series2_warming['My_bsub[Am2]'], 'bo-',
         label='My warming')
plt.plot(Ikon_series2_warming['Meas_T[K]'], Ikon_series2_warming['Mz_bsub[Am2]'], 'go-',
         label='Mz warming')
plt.ylabel('Magnetization (x10$^-6$ Am$^2$)')
plt.ticklabel_format(style='sci', scilimits=(0,0), axis='y')
plt.xlabel('Temperature (K)')
plt.legend(bbox_to_anchor=(1.05, 1), loc=2, borderaxespad=0.)
plt.title('IKON magnetite (series 2 experiment)')
plt.savefig('code_output/Ikon_magnetite_series2.pdf')
plt.show()

plt.figure(figsize=(4,4),dpi=160)
plt.plot(Ikon_series3_cooling['Meas_T[K]'], Ikon_series3_cooling['Mx_bsub[Am2]'], 'rs-',
         label='Mx cooling')
plt.plot(Ikon_series3_cooling['Meas_T[K]'], Ikon_series3_cooling['My_bsub[Am2]'], 'bs-',
         label='My cooling')
plt.plot(Ikon_series3_cooling['Meas_T[K]'], Ikon_series3_cooling['Mz_bsub[Am2]'], 'gs-',
         label='Mz cooling')
plt.plot(Ikon_series3_warming['Meas_T[K]'], Ikon_series3_warming['Mx_bsub[Am2]'], 'ro-',
         label='Mx warming')
plt.plot(Ikon_series3_warming['Meas_T[K]'], Ikon_series3_warming['My_bsub[Am2]'], 'bo-',
         label='My cooling')
plt.plot(Ikon_series3_warming['Meas_T[K]'], Ikon_series3_warming['Mz_bsub[Am2]'], 'go-',
         label='Mz warming')
plt.ylabel('Magnetization (x10$^-6$ Am$^2$)')
plt.ticklabel_format(style='sci', scilimits=(0,0), axis='y')
plt.xlabel('Temperature (K)')
plt.legend(bbox_to_anchor=(1.05, 1), loc=2, borderaxespad=0.)
plt.title('IKON magnetite (series 3 experiment)')
plt.show()
```

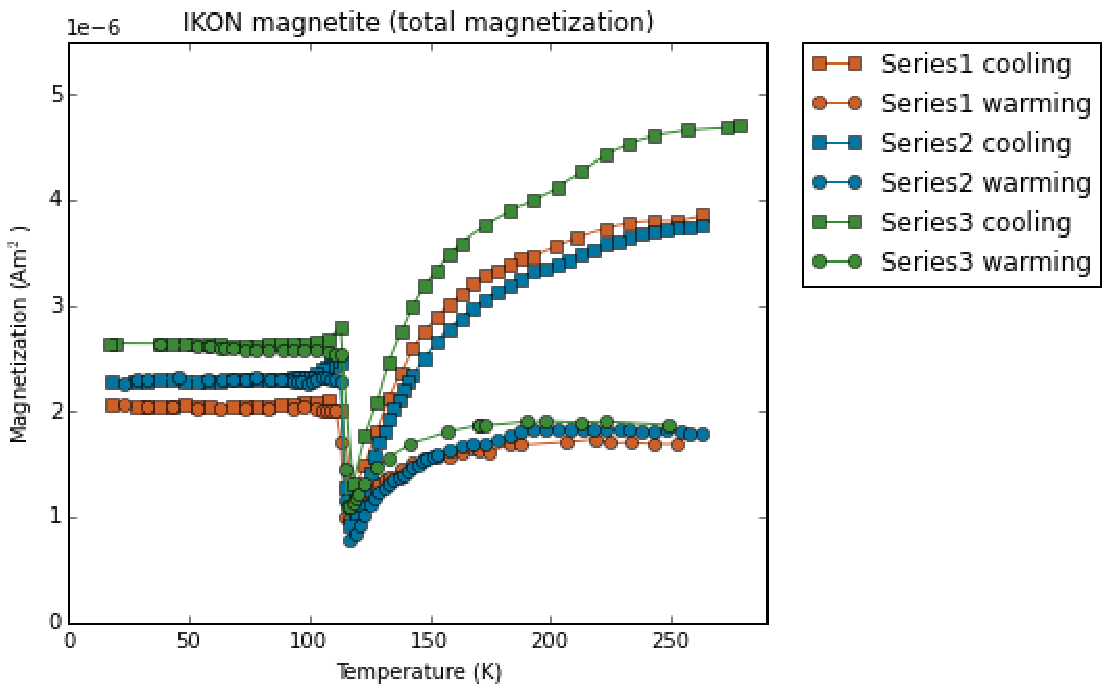

IKON magnetite (series 1 experiment)
1e−6
Magnetization (x10− 6 Am²)
Temperature (K)
Mx cooling
My cooling
Mz cooling
Mx warming
My warming
Mz warming


IKON magnetite (series 2 experiment)
1e−6
Magnetization (x10− 6 Am²)
Temperature (K)
Mx cooling
My cooling
Mz cooling
Mx warming
My warming
Mz warming



The total moment as calculated from the 3-axis data is plotted below in a single plot that shows all three experiments.

```
In [20]: plt.figure(figsize=(6,5),dpi=160)
         plt.plot(Ikon_series1_cooling['Meas_T[K]'], Ikon_series1_cooling['Mtotal_bsub[Am2]'], 's-',
                  label='Series1 cooling',color='#CD5F28')
         plt.plot(Ikon_series1_warming['Meas_T[K]'], Ikon_series1_warming['Mtotal_bsub[Am2]'], 'o-',
                  label='Series1 warming',color='#CD5F28')
         plt.plot(Ikon_series2_cooling['Meas_T[K]'], Ikon_series2_cooling['Mtotal_bsub[Am2]'], 's-',
                  label='Series2 cooling',color='#0077A2')
         plt.plot(Ikon_series2_warming['Meas_T[K]'], Ikon_series2_warming['Mtotal_bsub[Am2]'], 'o-',
                  label='Series2 warming',color='#0077A2')
         plt.plot(Ikon_series3_cooling['Meas_T[K]'], Ikon_series3_cooling['Mtotal_bsub[Am2]'], 's-',
                  label='Series3 cooling',color='#3B8B36')
         plt.plot(Ikon_series3_warming['Meas_T[K]'], Ikon_series3_warming['Mtotal_bsub[Am2]'], 'o-',
                  label='Series3 warming',color='#3B8B36')

         plt.ylabel('Magnetization (Am$^2$)')
         plt.xlabel('Temperature (K)')
         plt.xlim(0, 290)
         plt.ylim(0, .0000055)
         plt.ticklabel_format(style='sci', scilimits=(0,0), axis='y')
         plt.legend(bbox_to_anchor=(1.05, 1), loc=2, borderaxespad=0.)
         plt.title('IKON magnetite (total magnetization)')
         plt.savefig('code_output/Ikon_magnetite_total.pdf')
         plt.show()
```



The remanence lost in each experiment between 260 K and just prior to the Verwey transition increase.

```
In [21]: series1_260 = Ikon_series1_cooling['Mtotal_bsub[Am2]'][0]
         series2_260 = Ikon_series2_cooling['Mtotal_bsub[Am2]'][0]
         series3_260 = Ikon_series3_cooling['Mtotal_bsub[Am2]'][2]
         series1_min = Ikon_series1_cooling['Mtotal_bsub[Am2]'].min()
         series2_min = Ikon_series2_cooling['Mtotal_bsub[Am2]'].min()
         series3_min = Ikon_series3_cooling['Mtotal_bsub[Am2]'].min()
         print 'Series 1 percent lost between 260K and minima'
         print ((series1_260-series1_min)/series1_260)*100
         print 'Series 2 percent lost between 260K and minima'
         print ((series2_260-series2_min)/series2_260)*100
         print 'Series 3 percent lost between 260K and minima'
         print ((series3_260-series3_min)/series3_260)*100
```

```
Series 1 percent lost between 260K and minima
67.8202160088
Series 2 percent lost between 260K and minima
75.1987424572
Series 3 percent lost between 260K and minima
71.7873125177
```

The remanence lost in each experiment between 260 K and the plateau following the Verwey transition increase.

```
In [22]: series1_260 = Ikon_series1_cooling['Mtotal_bsub[Am2]'][0]
         series2_260 = Ikon_series2_cooling['Mtotal_bsub[Am2]'][0]
         series3_260 = Ikon_series3_cooling['Mtotal_bsub[Am2]'][2]
         series1_50 = Ikon_series1_cooling['Mtotal_bsub[Am2]'][35]
         series2_50 = Ikon_series2_cooling['Mtotal_bsub[Am2]'][58]
```

```
series3_50 = Ikon_series3_cooling['Mtotal_bsub[Am2]'][33]
print 'Series 1 post-Verwey plateau remanence as percent of 260K remanence'
print (series1_50/series1_260)*100
print 'Series 2 post-Verwey plateau remanence as percent of 260K remanence'
print (series2_50/series2_260)*100
print 'Series 3 post-Verwey plateau remanence as percent of 260K remanence'
print (series3_50/series3_260)*100
```

```
Series 1 post-Verwey plateau remanence as percent of 260K remanence
53.4020260118
Series 2 post-Verwey plateau remanence as percent of 260K remanence
60.9993296955
Series 3 post-Verwey plateau remanence as percent of 260K remanence
56.4923557659
```

The remanence lost in each experiment following thermal cycling.

```
In [23]: series1_260_warming = Ikon_series1_warming['Mtotal_bsub[Am2]'][41]
         series2_260_warming = Ikon_series2_warming['Mtotal_bsub[Am2]'][63]
         series3_260_warming = Ikon_series3_warming['Mtotal_bsub[Am2]'][35]
         print 'Series 1 post-thermal cycling remanence (at 250-260K) as percent of 260K remanence'
         print (series1_260_warming/series1_260)*100
         print 'Series 2 post-thermal cycling remanence (at 250-260K) as percent of 260K remanence'
         print (series2_260_warming/series2_260)*100
         print 'Series 3 post-thermal cycling remanence (at 250-260K) as percent of 260K remanence'
         print (series3_260_warming/series3_260)*100
```

```
Series 1 post-thermal cycling remanence (at 250-260K) as percent of 260K remanence
43.8987720207
Series 2 post-thermal cycling remanence (at 250-260K) as percent of 260K remanence
47.7466227538
Series 3 post-thermal cycling remanence (at 250-260K) as percent of 260K remanence
40.1523508649
```

```
In [24]: Ikon_series3_warming
```

Out[24]:

	specimen	Meas_T[K]	Mx[Am2]	My[Am2]	Mz[Am2]	\
0	Ikon_magnetite_<100>_02	38	-0.000003	8.410000e-09	0.000000	
1	Ikon_magnetite_<100>_02	53	-0.000003	9.640000e-09	0.000000	
2	Ikon_magnetite_<100>_02	58	-0.000003	9.410000e-09	0.000000	
3	Ikon_magnetite_<100>_02	59	-0.000003	9.730000e-09	0.000000	
4	Ikon_magnetite_<100>_02	63	-0.000003	1.060000e-08	0.000000	
5	Ikon_magnetite_<100>_02	65	-0.000003	6.450000e-09	0.000000	
6	Ikon_magnetite_<100>_02	68	-0.000003	6.940000e-09	0.000000	
7	Ikon_magnetite_<100>_02	73	-0.000003	8.360000e-09	0.000000	
8	Ikon_magnetite_<100>_02	78	-0.000003	7.750000e-09	0.000000	
9	Ikon_magnetite_<100>_02	83	-0.000003	7.720000e-09	0.000000	
10	Ikon_magnetite_<100>_02	89	-0.000003	1.030000e-08	0.000000	
11	Ikon_magnetite_<100>_02	93	-0.000003	6.890000e-09	0.000001	
12	Ikon_magnetite_<100>_02	98	-0.000003	4.540000e-09	0.000001	
13	Ikon_magnetite_<100>_02	103	-0.000003	3.450000e-09	0.000001	
14	Ikon_magnetite_<100>_02	108	-0.000003	2.510000e-09	0.000001	
15	Ikon_magnetite_<100>_02	111	-0.000003	2.300000e-09	0.000001	
16	Ikon_magnetite_<100>_02	113	-0.000003	-3.230000e-09	0.000001	
17	Ikon_magnetite_<100>_02	115	-0.000001	-2.870000e-07	0.000001	

```
18  Ikon_magnetite_<100>_02       116 -0.000001 -2.000000e-07  0.000001
19  Ikon_magnetite_<100>_02       117 -0.000001 -2.080000e-07  0.000001
20  Ikon_magnetite_<100>_02       118 -0.000001 -2.180000e-07  0.000001
21  Ikon_magnetite_<100>_02       119 -0.000001 -2.320000e-07  0.000001
22  Ikon_magnetite_<100>_02       120 -0.000001 -2.420000e-07  0.000001
23  Ikon_magnetite_<100>_02       123 -0.000001 -2.430000e-07  0.000001
24  Ikon_magnetite_<100>_02       128 -0.000002 -2.750000e-07  0.000001
25  Ikon_magnetite_<100>_02       133 -0.000002 -3.030000e-07  0.000001
26  Ikon_magnetite_<100>_02       142 -0.000002 -3.240000e-07  0.000001
27  Ikon_magnetite_<100>_02       157 -0.000002 -3.590000e-07  0.000001
28  Ikon_magnetite_<100>_02       170 -0.000002 -3.700000e-07  0.000001
29  Ikon_magnetite_<100>_02       170 -0.000002 -3.710000e-07  0.000001
30  Ikon_magnetite_<100>_02       173 -0.000002 -3.730000e-07  0.000001
31  Ikon_magnetite_<100>_02       190 -0.000002 -3.850000e-07  0.000001
32  Ikon_magnetite_<100>_02       198 -0.000002 -3.880000e-07  0.000001
33  Ikon_magnetite_<100>_02       213 -0.000002 -3.970000e-07  0.000001
34  Ikon_magnetite_<100>_02       223 -0.000002 -4.050000e-07  0.000001
35  Ikon_magnetite_<100>_02       249 -0.000002 -4.150000e-07  0.000001

    Mtot [Am2]    Dec   Inc  Mx-bcorr      My-bcorr      ...        \
0     0.000003  179.8   9.5 -0.000003  3.430000e-08      ...
1     0.000003  179.8   9.9 -0.000003  3.740000e-08      ...
2     0.000003  179.8  10.0 -0.000003  3.780000e-08      ...
3     0.000003  179.8  10.0 -0.000003  3.830000e-08      ...
4     0.000003  179.8  10.1 -0.000003  3.960000e-08      ...
5     0.000003  179.9  10.3 -0.000003  3.570000e-08      ...
6     0.000003  179.8  10.4 -0.000003  3.660000e-08      ...
7     0.000003  179.8  10.5 -0.000003  3.860000e-08      ...
8     0.000003  179.8  10.6 -0.000003  3.860000e-08      ...
9     0.000003  179.8  10.7 -0.000003  3.920000e-08      ...
10    0.000003  179.8  10.7 -0.000003  4.260000e-08      ...
11    0.000003  179.8  10.9 -0.000003  3.960000e-08      ...
12    0.000003  179.9  11.3 -0.000003  3.790000e-08      ...
13    0.000003  179.9  11.4 -0.000003  3.740000e-08      ...
14    0.000003  179.9  11.7 -0.000003  3.710000e-08      ...
15    0.000003  179.9  11.8 -0.000003  3.730000e-08      ...
16    0.000003  180.1  12.0 -0.000003  3.200000e-08      ...
17    0.000002  191.1  27.0 -0.000001 -2.520000e-07      ...
18    0.000001  190.0  28.8 -0.000001 -1.640000e-07      ...
19    0.000001  190.5  29.0 -0.000001 -1.730000e-07      ...
20    0.000001  190.6  28.3 -0.000001 -1.820000e-07      ...
21    0.000001  190.9  27.9 -0.000001 -1.970000e-07      ...
22    0.000001  191.1  27.5 -0.000001 -2.060000e-07      ...
23    0.000002  190.3  26.3 -0.000001 -2.070000e-07      ...
24    0.000002  190.4  24.6 -0.000001 -2.380000e-07      ...
25    0.000002  190.8  23.2 -0.000002 -2.650000e-07      ...
26    0.000002  190.6  21.5 -0.000002 -2.850000e-07      ...
27    0.000002  191.0  20.5 -0.000002 -3.180000e-07      ...
28    0.000002  191.0  18.8 -0.000002 -3.280000e-07      ...
29    0.000002  191.1  20.2 -0.000002 -3.290000e-07      ...
30    0.000002  191.1  20.3 -0.000002 -3.300000e-07      ...
31    0.000002  191.2  20.7 -0.000002 -3.400000e-07      ...
32    0.000002  191.3  21.0 -0.000002 -3.420000e-07      ...
33    0.000002  191.6  21.7 -0.000002 -3.490000e-07      ...
```

34	0.000002	191.8	22.0	-0.000002	-3.560000e-07	...
35	0.000002	192.2	23.3	-0.000002	-3.630000e-07	...

	position[cm]	Drift_ratio	Ja/Jr	run#	description	Meas_T [K] \
0	NaN	NaN	0	NaN	NaN	38
1	NaN	NaN	0	NaN	NaN	53
2	NaN	NaN	0	NaN	NaN	58
3	NaN	NaN	0	NaN	NaN	59
4	NaN	NaN	0	NaN	NaN	63
5	NaN	NaN	0	NaN	NaN	65
6	NaN	NaN	0	NaN	NaN	68
7	NaN	NaN	0	NaN	NaN	73
8	NaN	NaN	0	NaN	NaN	78
9	NaN	NaN	0	NaN	NaN	83
10	NaN	NaN	0	NaN	NaN	89
11	NaN	NaN	0	NaN	NaN	93
12	NaN	NaN	0	NaN	NaN	98
13	NaN	NaN	0	NaN	NaN	103
14	NaN	NaN	0	NaN	NaN	108
15	NaN	NaN	0	NaN	NaN	111
16	NaN	NaN	0	NaN	NaN	113
17	NaN	NaN	0	NaN	NaN	115
18	NaN	NaN	0	NaN	NaN	116
19	NaN	NaN	0	NaN	NaN	117
20	NaN	NaN	0	NaN	NaN	118
21	NaN	NaN	0	NaN	NaN	119
22	NaN	NaN	0	NaN	NaN	120
23	NaN	NaN	0	NaN	NaN	123
24	NaN	NaN	0	NaN	NaN	128
25	NaN	NaN	0	NaN	NaN	133
26	NaN	NaN	0	NaN	NaN	142
27	NaN	NaN	0	NaN	NaN	157
28	NaN	NaN	0	NaN	NaN	170
29	NaN	NaN	0	NaN	NaN	170
30	NaN	NaN	0	NaN	NaN	173
31	NaN	NaN	0	NaN	NaN	190
32	NaN	NaN	0	NaN	NaN	198
33	NaN	NaN	0	NaN	NaN	213
34	NaN	NaN	0	NaN	NaN	223
35	NaN	NaN	0	NaN	NaN	249

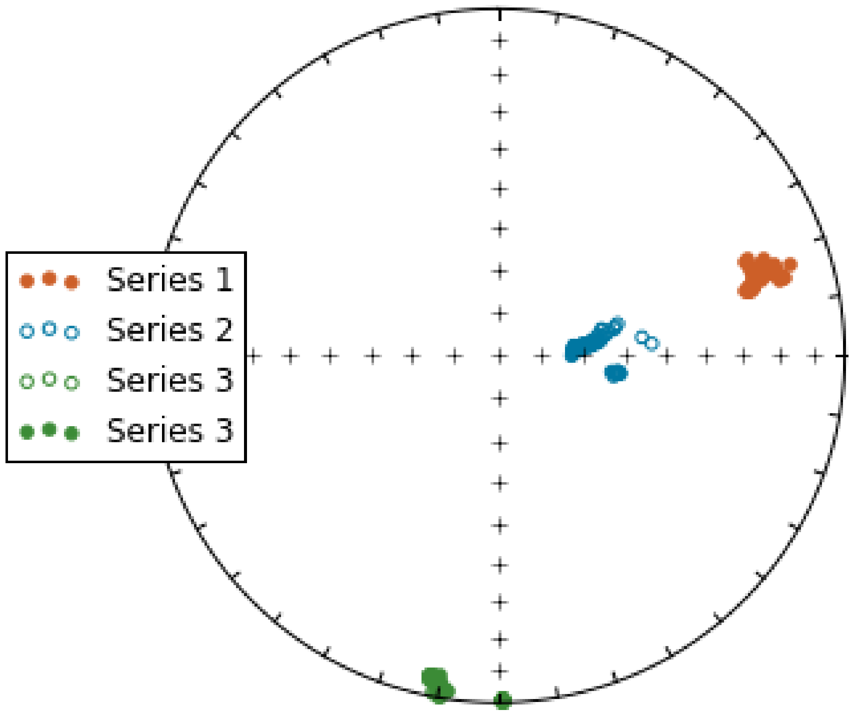
	Mx_bsub[Am2]	My_bsub[Am2]	Mz_bsub[Am2]	Mtotal_bsub[Am2]
0	-0.000003	3.758188e-08	-5.023969e-08	0.000003
1	-0.000003	3.901838e-08	-4.256805e-08	0.000003
2	-0.000003	3.877076e-08	-5.319375e-08	0.000003
3	-0.000003	3.901120e-08	-5.177319e-08	0.000003
4	-0.000003	3.978780e-08	-5.542831e-08	0.000003
5	-0.000003	3.565246e-08	-5.167098e-08	0.000003
6	-0.000003	3.604803e-08	-4.843337e-08	0.000003
7	-0.000003	3.776586e-08	-5.133377e-08	0.000003
8	-0.000003	3.808079e-08	-5.566409e-08	0.000003
9	-0.000003	3.833474e-08	-4.508982e-08	0.000003
10	-0.000003	4.009976e-08	-3.055821e-08	0.000003
11	-0.000003	3.660333e-08	-1.602101e-08	0.000003

```
12     -0.000003  3.346642e-08  1.588544e-08         0.000003
13     -0.000003  3.592538e-08 -1.975708e-08         0.000003
14     -0.000003  3.821011e-08 -4.514448e-08         0.000003
15     -0.000003  3.742928e-08 -3.849137e-08         0.000003
16     -0.000003  3.210114e-08 -3.743009e-08         0.000003
17     -0.000001 -2.514129e-07  1.738920e-07         0.000001
18     -0.000001 -1.644120e-07  5.267430e-08         0.000001
19     -0.000001 -1.724685e-07  5.323316e-08         0.000001
20     -0.000001 -1.824732e-07  5.740549e-08         0.000001
21     -0.000001 -1.963161e-07  6.901703e-08         0.000001
22     -0.000001 -2.058868e-07  7.089353e-08         0.000001
23     -0.000001 -2.038936e-07  6.241842e-08         0.000001
24     -0.000001 -2.311369e-07  3.167948e-08         0.000001
25     -0.000002 -2.581652e-07  1.484442e-08         0.000002
26     -0.000002 -2.784564e-07  1.137660e-09         0.000002
27     -0.000002 -3.097541e-07 -2.514542e-08         0.000002
28     -0.000002 -3.208927e-07 -6.900391e-08         0.000002
29     -0.000002 -3.218927e-07 -1.500391e-08         0.000002
30     -0.000002 -3.231767e-07 -1.602981e-08         0.000002
31     -0.000002 -3.291133e-07 -8.867275e-08         0.000002
32     -0.000002 -3.327938e-07 -6.578231e-08         0.000002
33     -0.000002 -3.407555e-07 -5.176920e-08         0.000002
34     -0.000002 -3.481065e-07 -5.027017e-08         0.000002
35     -0.000002 -3.562709e-07 -3.892691e-08         0.000002

[36 rows x 47 columns]
```

The directional data for the three experiments is plotted on a single equal area plot.

In [25]:
```python
directions_cart_series1_cooling=[]
directions_cart_series1_warming=[]

for n in range(len(Ikon_series1_cooling)):
    directions_cart_series1_cooling.append([Ikon_series1_cooling['Mx_bsub[Am2]'][n],
                                            Ikon_series1_cooling['My_bsub[Am2]'][n],
                                            Ikon_series1_cooling['Mz_bsub[Am2]'][n]])
for n in range(len(Ikon_series1_warming)):
    directions_cart_series1_warming.append([Ikon_series1_warming['Mx_bsub[Am2]'][n],
                                            Ikon_series1_warming['My_bsub[Am2]'][n],
                                            Ikon_series1_warming['Mz_bsub[Am2]'][n]])

directions_DI_series1_cooling=pmag.cart2dir(directions_cart_series1_cooling)
directions_DI_series1_warming=pmag.cart2dir(directions_cart_series1_warming)

directions_cart_series2_cooling=[]
directions_cart_series2_warming=[]

for n in range(len(Ikon_series2_cooling)):
    directions_cart_series2_cooling.append([Ikon_series2_cooling['Mx_bsub[Am2]'][n],
                                            Ikon_series2_cooling['My_bsub[Am2]'][n],
                                            Ikon_series2_cooling['Mz_bsub[Am2]'][n]])
for n in range(len(Ikon_series2_warming)):
    directions_cart_series2_warming.append([Ikon_series2_warming['Mx_bsub[Am2]'][n],
                                            Ikon_series2_warming['My_bsub[Am2]'][n],
                                            Ikon_series2_warming['Mz_bsub[Am2]'][n]])
```

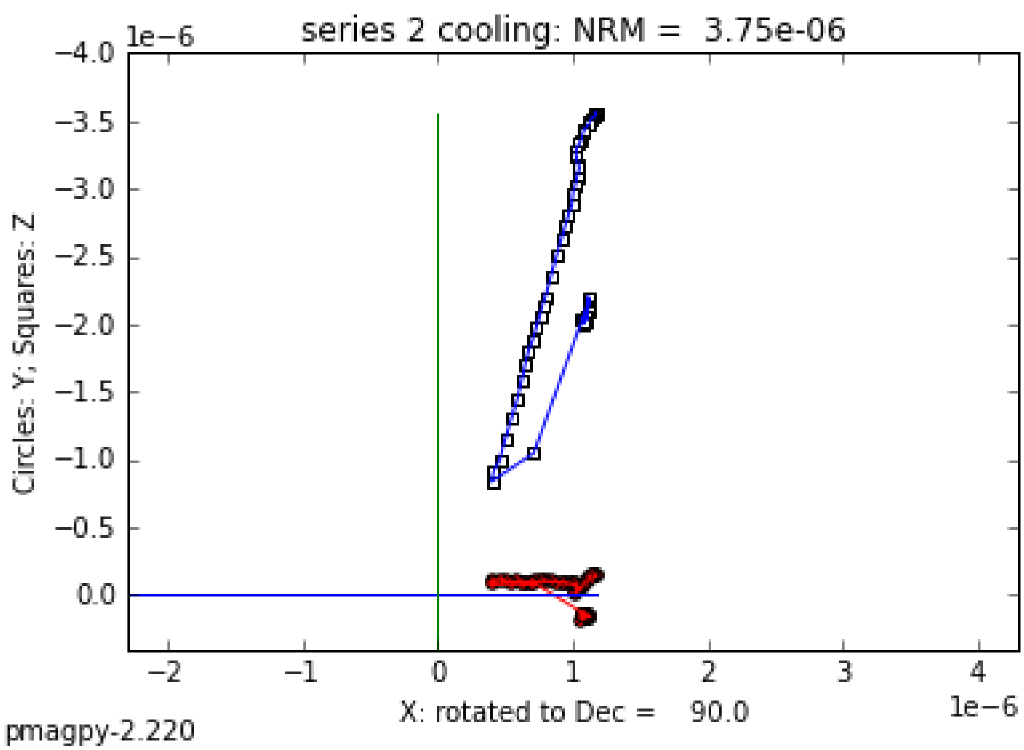
```
directions_DI_series2_cooling=pmag.cart2dir(directions_cart_series2_cooling)
directions_DI_series2_warming=pmag.cart2dir(directions_cart_series2_warming)

directions_cart_series3_cooling=[]
directions_cart_series3_warming=[]

for n in range(len(Ikon_series3_cooling)):
    directions_cart_series3_cooling.append([Ikon_series3_cooling['Mx_bsub[Am2]'][n],
                                            Ikon_series3_cooling['My_bsub[Am2]'][n],
                                            Ikon_series3_cooling['Mz_bsub[Am2]'][n]])
for n in range(len(Ikon_series3_warming)):
    directions_cart_series3_warming.append([Ikon_series3_warming['Mx_bsub[Am2]'][n],
                                            Ikon_series3_warming['My_bsub[Am2]'][n],
                                            Ikon_series3_warming['Mz_bsub[Am2]'][n]])

directions_DI_series3_cooling=pmag.cart2dir(directions_cart_series3_cooling)
directions_DI_series3_warming=pmag.cart2dir(directions_cart_series3_warming)

fignum = 1
plt.figure(num=fignum,figsize=(6,6),dpi=160)
pmagplotlib.plotNET(fignum)
IPmag.iplotDI(directions_DI_series1_cooling,color='#CD5F28', label='Series 1')
IPmag.iplotDI(directions_DI_series1_warming,color='#CD5F28')
IPmag.iplotDI(directions_DI_series2_cooling,color='#0077A2', label='Series 2')
IPmag.iplotDI(directions_DI_series2_warming,color='#0077A2')
IPmag.iplotDI(directions_DI_series3_cooling,color='#3B8B36', label='Series 3')
IPmag.iplotDI(directions_DI_series3_warming,color='#3B8B36')
plt.legend(loc=6)
plt.savefig('code_output/Ikon_magnetite_EA.pdf')
plt.show()
```

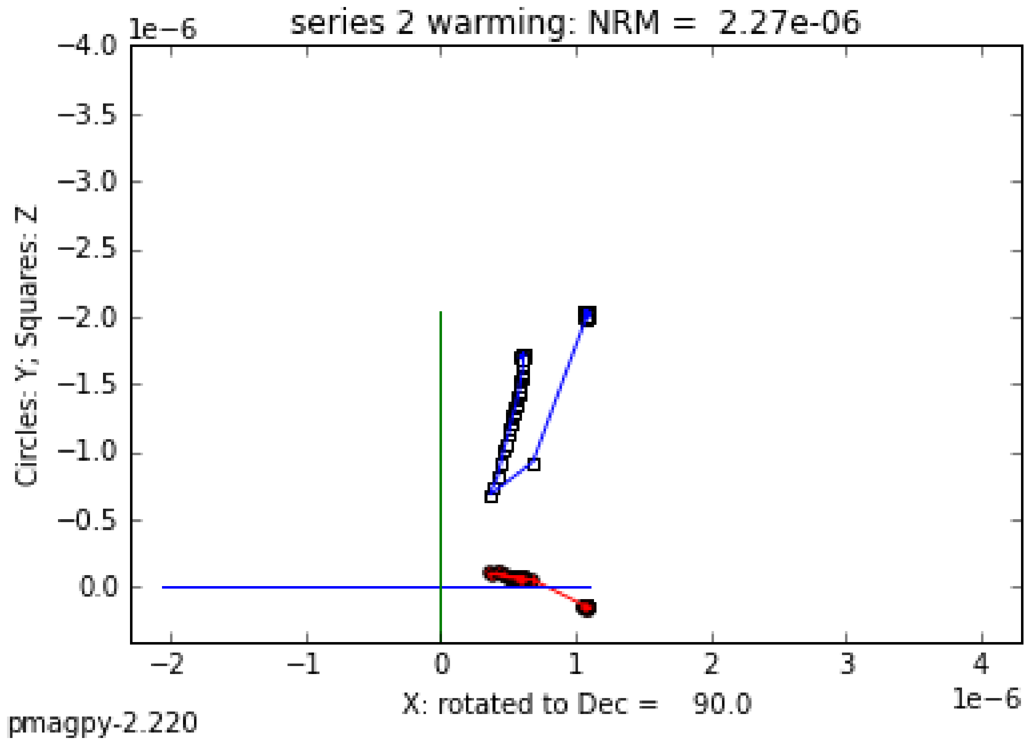


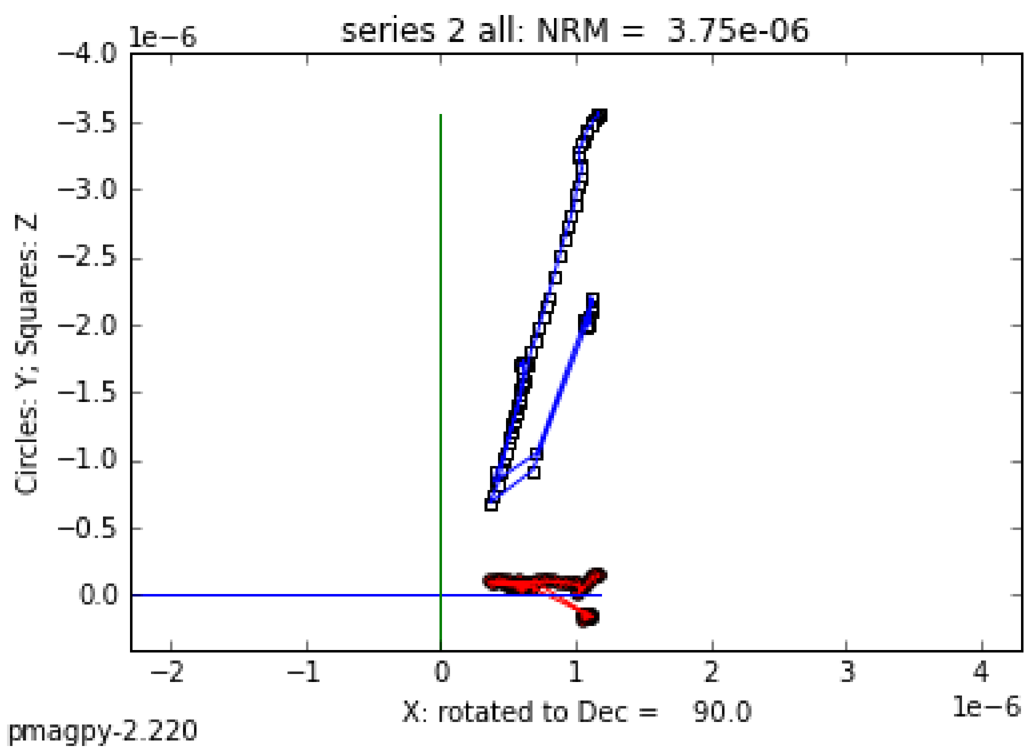
There are some quite interesting directional changes in the Series 2 data set. The data from that experiment is plotted below on Zijderveld plots.

```
In [26]: #make a datablock with this format: [treatment step, dec, inc, intensity]
         datablock_cooling=[]
         for n in range(0,len(Ikon_series2_cooling)):
             datablock_cooling.append([Ikon_series2_cooling['Meas_T[K]'][n],
                                  directions_DI_series2_cooling[n][0],
                                  directions_DI_series2_cooling[n][1],
                                  directions_DI_series2_cooling[n][2]])
         datablock_warming=[]
         for n in range(0,len(Ikon_series2_warming)):
             datablock_warming.append([Ikon_series2_warming['Meas_T[K]'][n],
                                  directions_DI_series2_warming[n][0],
                                  directions_DI_series2_warming[n][1],
                                  directions_DI_series2_warming[n][2]])
```

```
datablock_all=datablock_cooling+datablock_warming

#plot with pmagplotlib.plotZ(fignum,datablock,angle,s,norm)
fignum = 1
pmagplotlib.plotZ(1,datablock_cooling,90,'series 2 cooling',0)
plt.ticklabel_format(style='sci', scilimits=(0,0), axis='y')
plt.ticklabel_format(style='sci', scilimits=(0,0), axis='x')
plt.ylim(.0000004,-.000004,)
plt.xlim(0,.000002,)
plt.savefig('code_output/Ikon_magnetite_series2_zplot_cooling.pdf')
plt.show()

fignum = 2
pmagplotlib.plotZ(1,datablock_warming,90,'series 2 warming',0)
plt.ticklabel_format(style='sci', scilimits=(0,0), axis='y')
plt.ticklabel_format(style='sci', scilimits=(0,0), axis='x')
plt.ylim(.0000004,-.000004,)
plt.xlim(0,.000002,)
plt.savefig('code_output/Ikon_magnetite_series2_zplot_warming.pdf')
plt.show()

fignum = 3
pmagplotlib.plotZ(1,datablock_all,90,'series 2 all',0)
plt.ticklabel_format(style='sci', scilimits=(0,0), axis='y')
plt.ticklabel_format(style='sci', scilimits=(0,0), axis='x')
plt.ylim(.0000004,-.000004,)
plt.xlim(0,.000002,)
plt.savefig('code_output/Ikon_magnetite_series2_zplot.pdf')
plt.show()
```




series 2 warming: NRM = 2.27e-06
1e−6
−4.0
−3.5
−3.0
−2.5
−2.0
−1.5
−1.0
−0.5
0.0
Circles: Y; Squares: Z
−2
−1
0
1
2
3
4
X: rotated to Dec = 90.0
1e−6
pmagpy-2.220


series 2 all: NRM = 3.75e-06
1e−6
−4.0
−3.5
−3.0
−2.5
−2.0
−1.5
−1.0
−0.5
0.0
Circles: Y; Squares: Z
−2
−1
0
1
2
3
4
X: rotated to Dec = 90.0
1e−6
pmagpy-2.220

5 Polycrystalline magnetite and hematite experiments

This sample is from a product marketed as "Nature Company hematite" (referred to as naco in the code and the data folder) that is a polycrystalline mix of hematite with magnetite impurity. Low-temperature cycling experiments on this specimen (cf-naco-1) were conducted on the IRM-LTI and the MPMS. The two cells below import these data into dataframes.

In [27]:
```
Naco_cooling = pd.read_csv('../Data/NaCo/Naco_cooling.csv')
Naco_warming = pd.read_csv('../Data/NaCo/Naco_warming.csv')
Naco_cooling.head()
```

Out[27]:
```
     specimen   Mx[Am2]       My[Am2]   Mz[Am2]   MN[Am2]       ME[Am2]  \
0  cf-naco-1  0.000083 -4.335590e-08 -0.000003  0.000083 -4.335590e-08
1  cf-naco-1  0.000083 -4.275720e-08 -0.000003  0.000083 -4.275720e-08
2  cf-naco-1  0.000083 -4.030780e-08 -0.000003  0.000083 -4.030780e-08
3  cf-naco-1  0.000083 -5.599900e-08 -0.000003  0.000083 -5.599900e-08
4  cf-naco-1  0.000083 -5.100280e-08 -0.000003  0.000083 -5.100280e-08

    MV[Am2]  Mtot[Am2]  Dec[deg]  Inc[deg]    ...           time  series  \
0 -0.000003   0.000083 -0.029839  -2.17446    ...     10:41:36 AM       1
1 -0.000003   0.000083 -0.029466  -2.18214    ...     10:45:05 AM       1
2 -0.000003   0.000083 -0.027778  -2.17731    ...     10:46:28 AM       1
3 -0.000003   0.000083 -0.038592  -2.18009    ...     10:48:48 AM       1
4 -0.000003   0.000083 -0.035174  -2.17820    ...     11:32:19 AM       1

   position[cm]  Drift_ratio  Ja/Jr  run#  Description  Meas_T[K]      Mode  \
0           NaN          NaN      0   NaN      292.893     291.28  DISCRETE
1           NaN          NaN      0   NaN      292.920     291.26  DISCRETE
2           NaN          NaN      0   NaN      292.929     291.26  DISCRETE
3           NaN          NaN      0   NaN      284.969     291.23  DISCRETE
4           NaN          NaN      0   NaN      181.799     290.19  DISCRETE

   Type
0   NaN
1   NaN
2   NaN
3   NaN
4   NaN

[5 rows x 35 columns]
```

In [28]:
```
Naco_MPMS = pd.read_csv('../Data/NaCo/Naco_MPMS.csv',header=3)
Naco_MPMS.head()
```

Out[28]:
```
      T [K]  Bapp [T]  M [Am2/kg]   reg fit              timestamp  Unnamed: 5  \
0       NaN       NaN         NaN       NaN                    NaN         NaN
1  300.0231         0    0.744367  0.974488  5/27/2011 2:06:42 PM         NaN
2  294.4838         0    0.744338  0.974525  5/27/2011 2:10:08 PM         NaN
3  289.3426         0    0.742235  0.974490  5/27/2011 2:11:13 PM         NaN
4  284.1801         0    0.739180  0.974057  5/27/2011 2:12:05 PM         NaN
```

```
     T [K].1  Bapp [T].1  M [Am2/kg].1  reg fit.1          timestamp.1
0        NaN         NaN           NaN        NaN                  NaN
1   14.99718           0      0.079222   0.974658  5/27/2011 3:28:22 PM
2   20.55822           0      0.079240   0.974714  5/27/2011 3:29:41 PM
3   25.55299           0      0.079243   0.974558  5/27/2011 3:30:42 PM
4   30.67751           0      0.079225   0.974482  5/27/2011 3:31:44 PM
```

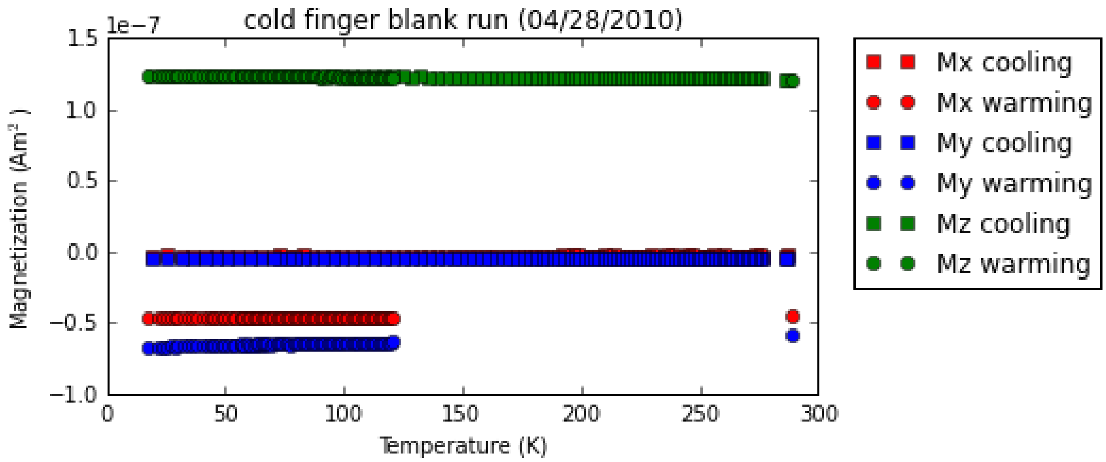
A blank run with the probe empty was done close in time to the experiment on the cf-naco-a specimen. That data is imported below into a dataframe and then plotted to determine the best way to background subtract the probe measurement from the sample data.

```
In [29]: blank_naco_data_cooling = pd.read_csv('../Data/NaCo/20110520cf_blank_cooling.csv')
         blank_naco_data_warming = pd.read_csv('../Data/NaCo/20110520cf_blank_warming.csv')
         blank_naco_data_warming.head()
```

```
Out[29]:    specimen       Mx[Am2]       My[Am2]  Mz[Am2]  MN[Am2]       ME[Am2]  \
         0  CF-blank -4.684120e-08 -6.720820e-08        0        0 -6.720820e-08
         1  CF-blank -4.699740e-08 -6.693490e-08        0        0 -6.693490e-08
         2  CF-blank -4.690780e-08 -6.685280e-08        0        0 -6.685280e-08
         3  CF-blank -4.700080e-08 -6.680970e-08        0        0 -6.680970e-08
         4  CF-blank -4.673360e-08 -6.666500e-08        0        0 -6.666500e-08

                 MV[Am2]  Mtot[Am2]  Dec[deg]  Inc[deg]    ...          time  series  \
         0  4.684120e-08          0  -28.5181   18.4050    ...    1:17:33 PM       7
         1  4.699740e-08          0  -28.4446   18.4917    ...    1:18:19 PM       7
         2  4.690780e-08          0  -28.4037   18.4572    ...    1:19:10 PM       7
         3  4.700080e-08          0  -28.4008   18.5009    ...    1:20:15 PM       7
         4  4.673360e-08          0  -28.3368   18.4045    ...    1:21:35 PM       7

            position[cm]  Drift_ratio  Ja/Jr  run#  Description  Meas_T[K]      Mode  \
         0           NaN          NaN      0   NaN       15.227      17.63  DISCRETE
         1           NaN          NaN      0   NaN       18.948      22.16  DISCRETE
         2           NaN          NaN      0   NaN       20.988      24.07  DISCRETE
         3           NaN          NaN      0   NaN       22.501      25.58  DISCRETE
         4           NaN          NaN      0   NaN       23.577      27.08  DISCRETE

            Type
         0   NaN
         1   NaN
         2   NaN
         3   NaN
         4   NaN

         [5 rows x 35 columns]
```

```
In [30]: blank_naco_data_cooling = pd.read_csv('../Data/NaCo/20110520cf_blank_cooling.csv')
         blank_naco_data_warming = pd.read_csv('../Data/NaCo/20110520cf_blank_warming.csv')
         blank_naco_data_warming.head()
         fignum=1
         plt.figure(num=fignum,figsize=(6,3),dpi=160)
         plt.plot(blank_naco_data_cooling['Meas_T[K]'], blank_naco_data_cooling['Mx[Am2]'], 'rs',
                  label='Mx cooling')
         plt.plot(blank_naco_data_warming['Meas_T[K]'], blank_naco_data_warming['Mx[Am2]'], 'ro',
                  label='Mx warming')
         plt.plot(blank_naco_data_cooling['Meas_T[K]'], blank_naco_data_cooling['My[Am2]'], 'bs',
```

```
            label='My cooling')
plt.plot(blank_naco_data_warming['Meas_T[K]'], blank_naco_data_warming['My[Am2]'], 'bo',
            label='My warming')
plt.plot(blank_naco_data_cooling['Meas_T[K]'], blank_naco_data_cooling['Mz[Am2]'], 'gs',
            label='Mz cooling')
plt.plot(blank_naco_data_warming['Meas_T[K]'], blank_naco_data_warming['Mz[Am2]'], 'go',
            label='Mz warming')

plt.ylabel('Magnetization (Am$^2$)')
plt.xlabel('Temperature (K)')
plt.legend(bbox_to_anchor=(1.05, 1), loc=2, borderaxespad=0.)
plt.title('cold finger blank run (04/28/2010)')

plt.show()
```



The cooling run was completed in full for the blank while there were gaps in the warming data. Let's use the cooling data which looks to be reversible for the z (while there is an unexplained offset in the y and z) for the background correction using the background_subtraction() function.

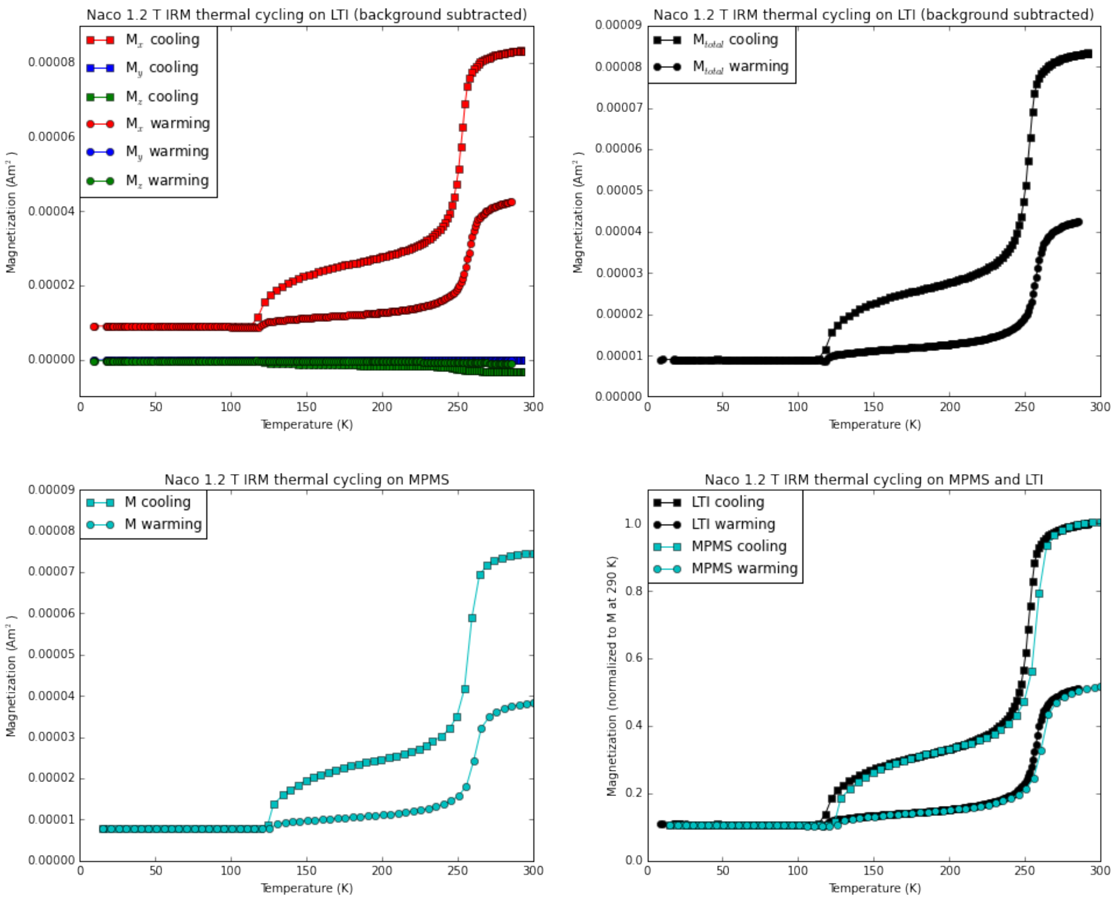
```
In [31]: #For the interpolate function to work the x values (temperature) need to be ascending.
         #The blank_hem_data_cooling can be sorted so that temperatures are ascending
         blank_naco_data_cooling = blank_naco_data_cooling.sort(['Meas_T[K]'])

         Naco_cooling['Mx_bsub[Am2]'] = background_sub(blank_naco_data_cooling['Mx[Am2]'],
                                                       blank_naco_data_cooling['Meas_T[K]'],
                                                       Naco_cooling['Mx[Am2]'],
                                                       Naco_cooling['Meas_T[K]'])

         Naco_cooling['My_bsub[Am2]'] = background_sub(blank_naco_data_cooling['My[Am2]'],
                                                       blank_naco_data_cooling['Meas_T[K]'],
                                                       Naco_cooling['My[Am2]'],
                                                       Naco_cooling['Meas_T[K]'])

         Naco_cooling['Mz_bsub[Am2]'] = background_sub(blank_naco_data_cooling['Mz[Am2]'],
                                                       blank_naco_data_cooling['Meas_T[K]'],
                                                       Naco_cooling['Mz[Am2]'],
                                                       Naco_cooling['Meas_T[K]'])
```

```
Naco_cooling['Mtotal_bsub[Am2]'] = np.sqrt(Naco_cooling['Mx_bsub[Am2]']**2 +
                                           Naco_cooling['My_bsub[Am2]']**2 +
                                           Naco_cooling['Mz_bsub[Am2]']**2)

Naco_warming['Mx_bsub[Am2]'] = background_sub(blank_naco_data_cooling['Mx[Am2]'],
                                              blank_naco_data_cooling['Meas_T[K]'],
                                              Naco_warming['Mx[Am2]'],
                                              Naco_warming['Meas_T[K]'])

Naco_warming['My_bsub[Am2]'] = background_sub(blank_naco_data_cooling['My[Am2]'],
                                              blank_naco_data_cooling['Meas_T[K]'],
                                              Naco_warming['My[Am2]'],
                                              Naco_warming['Meas_T[K]'])

Naco_warming['Mz_bsub[Am2]'] = background_sub(blank_naco_data_cooling['Mz[Am2]'],
                                              blank_naco_data_cooling['Meas_T[K]'],
                                              Naco_warming['Mz[Am2]'],
                                              Naco_warming['Meas_T[K]'])

Naco_warming['Mtotal_bsub[Am2]'] = np.sqrt(Naco_warming['Mx_bsub[Am2]']**2 +
                                           Naco_warming['My_bsub[Am2]']**2 +
                                           Naco_warming['Mz_bsub[Am2]']**2)
```

Having subtracted the holder off of the LTI experiment data, the background subtracted data is plotted below along with the data acquired during the low-temperature cycling experiment on the MPMS.

In [32]:
```
adjustprops = dict(left=0.1, bottom=0.1, right=0.97, top=0.93, wspace=0.25, hspace=0.25)
fig=plt.figure(figsize=(14,12),dpi=160)
fig.subplots_adjust(**adjustprops)
ax1 = plt.subplot(221)

ax1.plot(Naco_cooling['Meas_T[K]'], Naco_cooling['Mx_bsub[Am2]'], 'rs-',label='M$_x$ cooling')
ax1.plot(Naco_cooling['Meas_T[K]'], Naco_cooling['My_bsub[Am2]'], 'bs-',label='M$_y$ cooling')
ax1.plot(Naco_cooling['Meas_T[K]'], Naco_cooling['Mz_bsub[Am2]'], 'gs-',label='M$_z$ cooling')
ax1.plot(Naco_warming['Meas_T[K]'], Naco_warming['Mx_bsub[Am2]'], 'ro-',label='M$_x$ warming')
ax1.plot(Naco_warming['Meas_T[K]'], Naco_warming['My_bsub[Am2]'], 'bo-',label='M$_y$ warming')
ax1.plot(Naco_warming['Meas_T[K]'], Naco_warming['Mz_bsub[Am2]'], 'go-',label='M$_z$ warming')
plt.legend(loc=2, borderaxespad=0.)
plt.ylabel('Magnetization (Am$^2$)')
plt.xlabel('Temperature (K)')
plt.title('Naco 1.2 T IRM thermal cycling on LTI (background subtracted)')

ax2 = plt.subplot(222)
ax2.plot(Naco_cooling['Meas_T[K]'], Naco_cooling['Mtotal_bsub[Am2]'],
         'ks-',label='M$_{total}$ cooling')
ax2.plot(Naco_warming['Meas_T[K]'], Naco_warming['Mtotal_bsub[Am2]'],
         'ko-',label='M$_{total}$ warming')
plt.legend(loc=2, borderaxespad=0.)
plt.ylabel('Magnetization (Am$^2$)')
plt.xlabel('Temperature (K)')
plt.title('Naco 1.2 T IRM thermal cycling on LTI (background subtracted)')

ax3 = plt.subplot(223)
ax3.plot(Naco_MPMS['T [K]'],Naco_MPMS['M [Am2/kg]']/10000,'cs-',label='M cooling')
```

```
ax3.plot(Naco_MPMS['T [K].1'],Naco_MPMS['M [Am2/kg].1']/10000,'co-',label='M warming')
plt.legend(loc=2, borderaxespad=0.)
plt.ylabel('Magnetization (Am$^2$)')
plt.ylim(0,0.00009)
plt.xlabel('Temperature (K)')
plt.xlim(0,300)
plt.title('Naco 1.2 T IRM thermal cycling on MPMS')

ax4 = plt.subplot(224)
ax4.plot(Naco_cooling['Meas_T[K]'],
         Naco_cooling['Mtotal_bsub[Am2]']/Naco_cooling['Mtotal_bsub[Am2]'][0],
         'ks-',label='LTI cooling')
ax4.plot(Naco_warming['Meas_T[K]'],
         Naco_warming['Mtotal_bsub[Am2]']/Naco_cooling['Mtotal_bsub[Am2]'][0],
         'ko-',label='LTI warming')
ax4.plot(Naco_MPMS['T [K]'],
         Naco_MPMS['M [Am2/kg]']/Naco_MPMS['M [Am2/kg]'][3],
         'cs-',label='MPMS cooling')
ax4.plot(Naco_MPMS['T [K].1'],
         Naco_MPMS['M [Am2/kg].1']/Naco_MPMS['M [Am2/kg]'][3],
         'co-',label='MPMS warming')
plt.ylabel('Magnetization (normalized to M at 290 K)')
plt.xlabel('Temperature (K)')
plt.legend(loc=2, borderaxespad=0.)
plt.xlim(0,300)
plt.ylim(ymin=0)
plt.title('Naco 1.2 T IRM thermal cycling on MPMS and LTI')
plt.show()
```



The total magnetization between the LTI and MPMS are quite similiar. The values obtained on the LTI are slightly higher which could be associated with there being small off-axis components that were not resolved using the MPMS. The code block below displays the values of magnetization at ~290 degrees on both instrument. These values are written on the figure in the main manuscript.

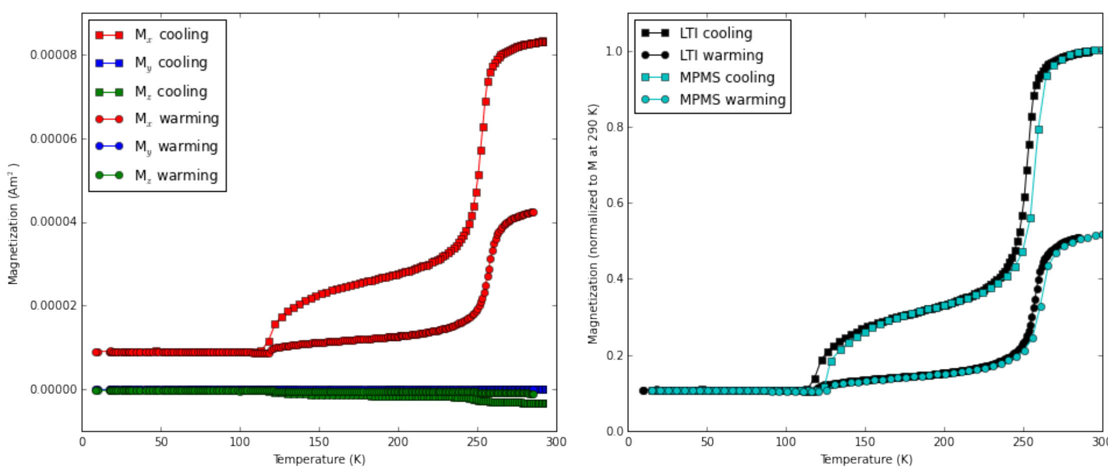
```
In [33]: #values quoted on figure
         a = Naco_cooling['Mtotal_bsub[Am2]'][0]
         b = Naco_cooling['Meas_T[K]'][5]
         print "For the temperature of", b, "on the LTI the magnetization is:", a, "Am2"
         c = Naco_MPMS['T [K]'][3]
         d = Naco_MPMS['M [Am2/kg]'][3]/10000
         print "For the temperature of", c, "on the MPMS the magnetization is:", d, "Am2"
         print "Number of data points collected during LTI run:", len(Naco_cooling['Meas_T[K]'])
```

```
For the temperature of 289.13 on the LTI the magnetization is: 8.33181600855e-05 Am2
For the temperature of 289.3426 on the MPMS the magnetization is: 7.422345e-05 Am2
Number of data points collected during LTI run: 114
```

A simplified version of the figure made above needs to be generated to use within the main manuscript.

```
In [34]: adjustprops = dict(left=0.1, bottom=0.1, right=0.97, top=0.93, wspace=0.15, hspace=0.1)
         fig=plt.figure(figsize=(14,6),dpi=160)
         fig.subplots_adjust(**adjustprops)
```

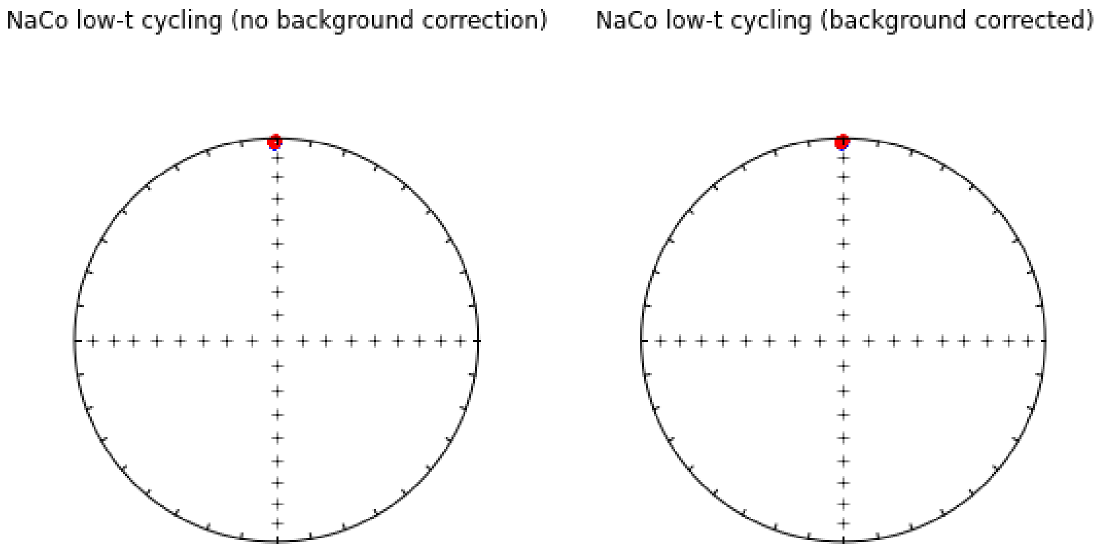
```
ax1 = plt.subplot(121)
ax1.plot(Naco_cooling['Meas_T[K]'], Naco_cooling['Mx_bsub[Am2]'], 'rs-',label='M$_x$ cooling')
ax1.plot(Naco_cooling['Meas_T[K]'], Naco_cooling['My_bsub[Am2]'], 'bs-',label='M$_y$ cooling')
ax1.plot(Naco_cooling['Meas_T[K]'], Naco_cooling['Mz_bsub[Am2]'], 'gs-',label='M$_z$ cooling')
ax1.plot(Naco_warming['Meas_T[K]'], Naco_warming['Mx_bsub[Am2]'], 'ro-',label='M$_x$ warming')
ax1.plot(Naco_warming['Meas_T[K]'], Naco_warming['My_bsub[Am2]'], 'bo-',label='M$_y$ warming')
ax1.plot(Naco_warming['Meas_T[K]'], Naco_warming['Mz_bsub[Am2]'], 'go-',label='M$_z$ warming')
plt.legend(loc=2)
plt.ylabel('Magnetization (Am$^2$)')
plt.xlabel('Temperature (K)')
#plt.title('thermal cycling on IRM-LTI (background subtracted)')

ax2 = plt.subplot(122)
ax2.plot(Naco_cooling['Meas_T[K]'],
         Naco_cooling['Mtotal_bsub[Am2]']/Naco_cooling['Mtotal_bsub[Am2]'][0],
         'ks-',label='LTI cooling')
ax2.plot(Naco_warming['Meas_T[K]'],
         Naco_warming['Mtotal_bsub[Am2]']/Naco_cooling['Mtotal_bsub[Am2]'][0],
         'ko-',label='LTI warming')
ax2.plot(Naco_MPMS['T [K]'],Naco_MPMS['M [Am2/kg]']/Naco_MPMS['M [Am2/kg]'][3],
         'cs-',label='MPMS cooling')
ax2.plot(Naco_MPMS['T [K].1'],Naco_MPMS['M [Am2/kg].1']/Naco_MPMS['M [Am2/kg]'][3],
         'co-',label='MPMS warming')
plt.ylabel('Magnetization (normalized to M at 290 K)')
plt.xlabel('Temperature (K)')
#plt.title('thermal cycling on IRM-LTI and MPMS')
plt.legend(loc=2)
plt.xlim(0,300)
plt.ylim(ymin=0)
plt.savefig('code_output/Naco_LTcycle.pdf')
plt.show()
```



The direction of the Naco specimen throughout thermal cycling on the LTI can be plotted on an equal area plot. A subsection of this equal area plot was included in the figure concerning the Naco hematite/magnetite specimen in the main text.

In [35]:
```
directions_cart_cooling=[]
directions_cart_warming=[]
```

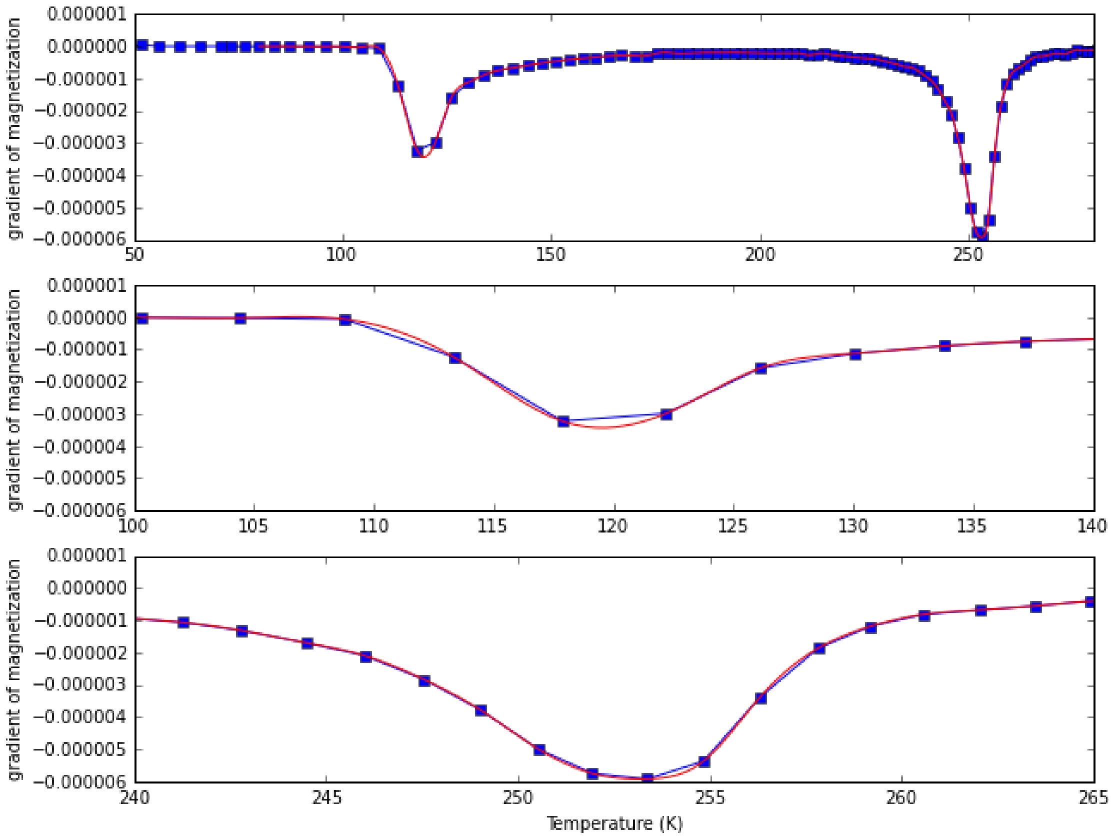
```
#data point 0 is oriented (remember python starts at 0)
for n in range(len(Naco_cooling)):
    directions_cart_cooling.append([Naco_cooling['Mx[Am2]'][n],
                                    Naco_cooling['My[Am2]'][n],
                                    Naco_cooling['Mz[Am2]'][n]])
for n in range(len(Naco_warming)):
    directions_cart_warming.append([Naco_warming['Mx[Am2]'][n],
                                    Naco_warming['My[Am2]'][n],
                                    Naco_warming['Mz[Am2]'][n]])

directions_DI_cooling=pmag.cart2dir(directions_cart_cooling)
directions_DI_warming=pmag.cart2dir(directions_cart_warming)

directions_cart_cooling=[]
directions_cart_warming=[]

#data point 0 is oriented (remember python starts at 0)
for n in range(len(Naco_cooling)):
    directions_cart_cooling.append([Naco_cooling['Mx_bsub[Am2]'][n],
                                    Naco_cooling['My_bsub[Am2]'][n],
                                    Naco_cooling['Mz_bsub[Am2]'][n]])
for n in range(len(Naco_warming)):
    directions_cart_warming.append([Naco_warming['Mx_bsub[Am2]'][n],
                                    Naco_warming['My_bsub[Am2]'][n],
                                    Naco_warming['Mz_bsub[Am2]'][n]])

directions_DI_cooling=pmag.cart2dir(directions_cart_cooling)
directions_DI_warming=pmag.cart2dir(directions_cart_warming)

fignum=1
fig=plt.figure(figsize=(8,5),dpi=160)
plt.subplot(121)
plt.figure(num=fignum,figsize=(8,8),dpi=160)
pmagplotlib.plotNET(fignum)
IPmag.iplotDI(directions_DI_cooling,'b')
IPmag.iplotDI(directions_DI_warming,'r')
plt.title('NaCo low-t cycling (no background correction)')

plt.subplot(122)
plt.figure(num=fignum,figsize=(8,8),dpi=160)
pmagplotlib.plotNET(fignum)
IPmag.iplotDI(directions_DI_cooling,'b')
IPmag.iplotDI(directions_DI_warming,'r')
plt.title('NaCo low-t cycling (background corrected)')
plt.savefig('code_output/Naco_directions.pdf')
plt.show()
```



In order to estimate the Morin and Verwey transition temperatures, the gradient of the cooling data can be plotted.

```
In [36]: gradient_LTI_cooling = np.gradient(Naco_cooling['Mtotal_bsub[Am2]'])

         from scipy.interpolate import interp1d

         #interpolate the data using a cubic spline
         f_LTI_cooling_inter =  interp1d(Naco_cooling['Meas_T[K]'][3:],
                                         gradient_LTI_cooling[3:],
                                         kind='cubic')

         xnew = np.linspace(80,280,1000)

         gradient_LTI_cooling_interpolated = f_LTI_cooling_inter(xnew)

         plt.figure(figsize=(10,8),dpi=160)
         plt.subplot(311)
         plt.plot(Naco_cooling['Meas_T[K]'], gradient_LTI_cooling,
                  'bs-',label='LTI gradient on cooling')
         plt.plot(xnew, gradient_LTI_cooling_interpolated, 'r-')
         plt.xlim(50, 280)
         plt.ylabel('gradient of magnetization')

         plt.subplot(312)
         plt.plot(Naco_cooling['Meas_T[K]'], gradient_LTI_cooling,
                  'bs-',label='LTI gradient on cooling')
         plt.plot(xnew, gradient_LTI_cooling_interpolated, 'r-')
         plt.xlim(100, 140)
         plt.ylabel('gradient of magnetization')
```

```
plt.subplot(313)
plt.plot(Naco_cooling['Meas_T[K]'], gradient_LTI_cooling,
         'bs-',label='LTI gradient on cooling')
plt.plot(xnew, gradient_LTI_cooling_interpolated, 'r-')
plt.xlim(240, 265)
plt.ylabel('gradient of magnetization')

plt.xlabel('Temperature (K)')
plt.show()
```




```
In [37]: LTI_morin = fmin(f_LTI_cooling_inter, x0=252)
         print 'The peak gradient for LTI cooling is at: ' + str(LTI_morin)
         print ""
         LTI_verwey = fmin(f_LTI_cooling_inter, x0=118)
         print 'The peak gradient for MPMS cooling is at: ' + str(LTI_verwey)
         print ""
```

```
Optimization terminated successfully.
         Current function value: -0.000006
         Iterations: 18
         Function evaluations: 36
The peak gradient for LTI cooling is at: [ 253.17009888]
```

```
Optimization terminated successfully.
         Current function value: -0.000003
         Iterations: 17
         Function evaluations: 34
The peak gradient for MPMS cooling is at: [ 119.51677246]
```

6 Pyrrhotite experiments

There were three experiments performed on this single crystal of pyrrhotite:

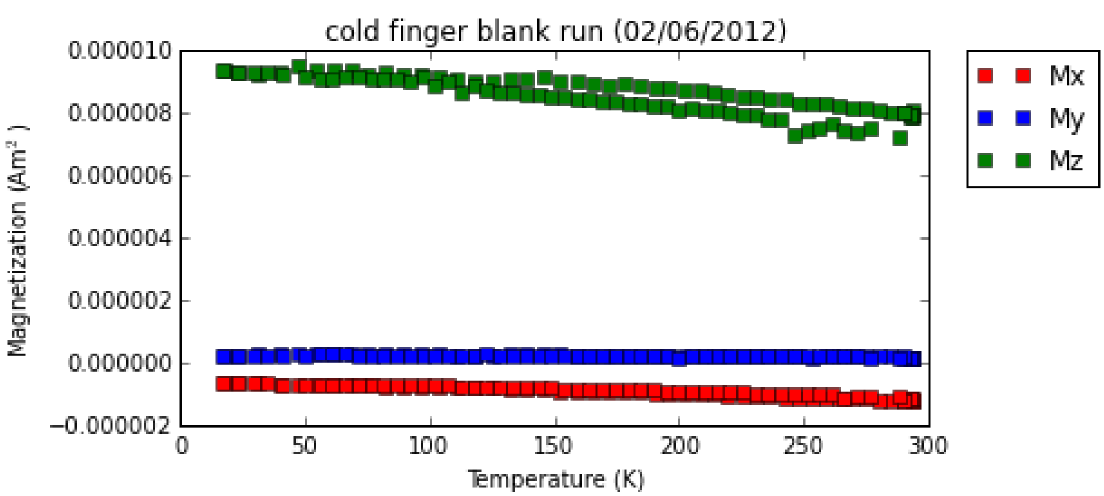
- an isothermal remanent magnetization bisecting the c and a_1 axes (series 5)
- an isothermal remanent magnetization along the c axis (series 6)
- an isothermal remanent magnetization bisecting the a_1 and -a_3 axes (series 7)

Import the data into a dataframe

```
In [38]: pyrrhotite_data = pd.read_csv('../Data/Pyrrhotite/Pyrrhotite_Experiments.csv')
```

A blank run of the empty coldfinger probe was conducted on 2/6/2012 (the day before the series 5 experiment). The data can be loaded into a dataframe.

```
In [39]: blank_for_pyrrhotite = pd.read_csv('../Data/Pyrrhotite/cf_blank.csv')

         plt.figure(figsize=(6,3),dpi=160)
         plt.plot(blank_for_pyrrhotite['measurement_T[K]'], blank_for_pyrrhotite['Mx[Am2]'], 'rs',
                  label='Mx')
         plt.plot(blank_for_pyrrhotite['measurement_T[K]'], blank_for_pyrrhotite['My[Am2]'], 'bs',
                  label='My')
         plt.plot(blank_for_pyrrhotite['measurement_T[K]'], blank_for_pyrrhotite['Mz[Am2]'], 'gs',
                  label='Mz')
         plt.ylabel('Magnetization (Am$^2$)')
         plt.xlabel('Temperature (K)')
         plt.legend(bbox_to_anchor=(1.05, 1), loc=2, borderaxespad=0.)
         plt.title('cold finger blank run (02/06/2012)')
         plt.show()
```



The probe magnetization appears to be largely reversible. Let's use the values upon cooling of the blank probe for the background correction of the pyrrhotite experimental data.

```
In [40]: blank_for_pyrrhotite_cooling = blank_for_pyrrhotite[0:51]
         blank_for_pyrrhotite_cooling = blank_for_pyrrhotite_cooling.sort(['measurement_T[K]'])

         pyrrhotite_data['Mx_bsub[Am2]'] = background_sub(blank_for_pyrrhotite_cooling['Mx[Am2]'],
                                                          blank_for_pyrrhotite_cooling['measurement_T[K
                                                          pyrrhotite_data['Mx[Am2]'],
                                                          pyrrhotite_data['Meas_T[K]'])
         pyrrhotite_data['My_bsub[Am2]'] = background_sub(blank_for_pyrrhotite_cooling['My[Am2]'],
                                                          blank_for_pyrrhotite_cooling['measurement_T[K
                                                          pyrrhotite_data['My[Am2]'],
                                                          pyrrhotite_data['Meas_T[K]'])
         pyrrhotite_data['Mz_bsub[Am2]'] = background_sub(blank_for_pyrrhotite_cooling['Mz[Am2]'],
                                                          blank_for_pyrrhotite_cooling['measurement_T[K
                                                          pyrrhotite_data['Mz[Am2]'],
                                                          pyrrhotite_data['Meas_T[K]'])

         pyrrhotite_data['Mtotal_bsub[Am2]'] = np.sqrt(pyrrhotite_data['Mx_bsub[Am2]']**2 +
                                                       pyrrhotite_data['My_bsub[Am2]']**2 +
                                                       pyrrhotite_data['Mz_bsub[Am2]']**2)
```

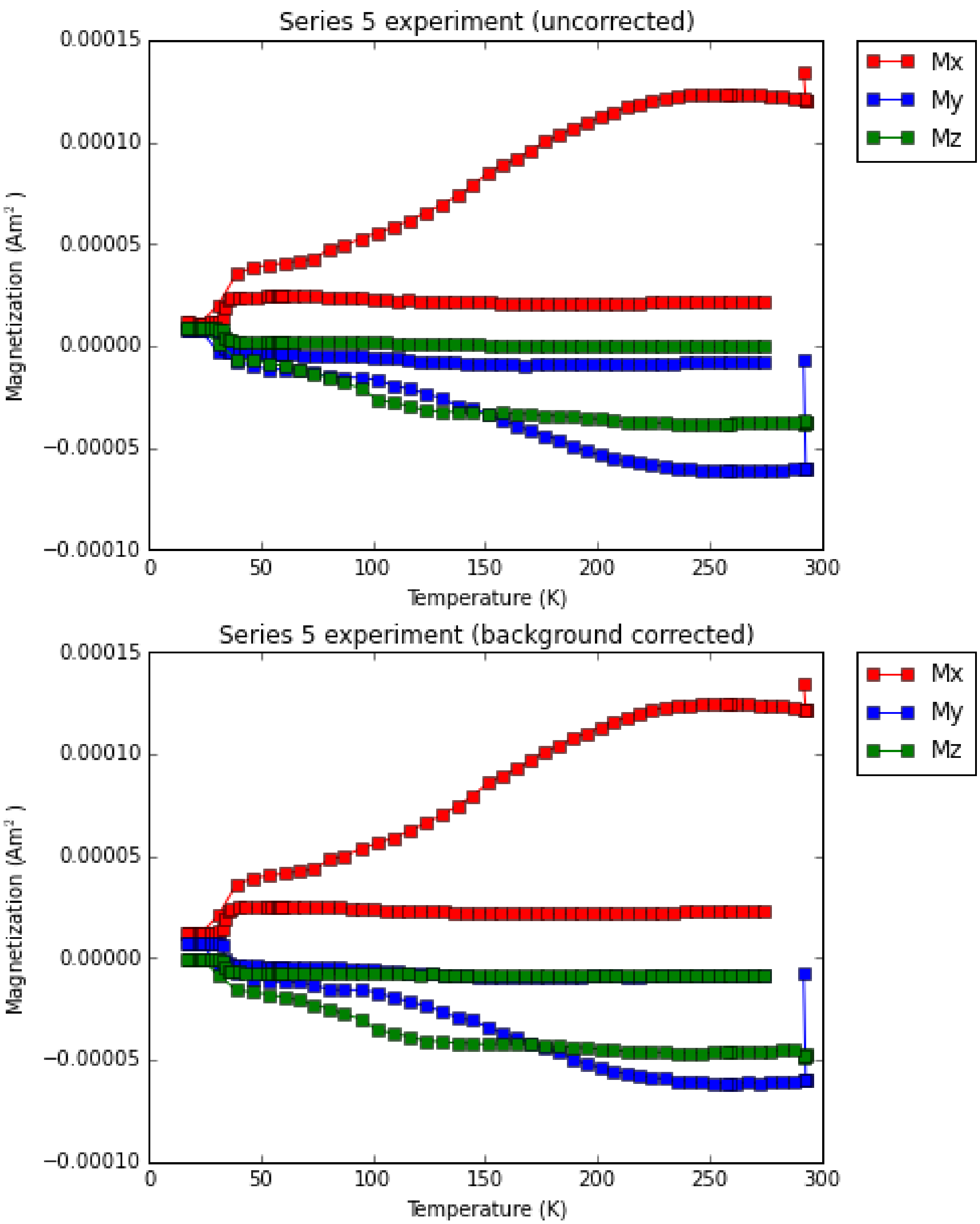
Split the data into series 5, 6 and 7.

```
In [41]: pyrrhotite_data_series5 = pyrrhotite_data.ix[pyrrhotite_data.series==5]
         pyrrhotite_data_series6 = pyrrhotite_data.ix[pyrrhotite_data.series==6]
         pyrrhotite_data_series6.reset_index(inplace=True)
         pyrrhotite_data_series7 = pyrrhotite_data.ix[pyrrhotite_data.series==7]
         pyrrhotite_data_series7.reset_index(inplace=True)
         pyrrhotite_data_series7.head()
```

```
Out[41]:    index            specimen   Mx[Am2]   My[Am2]   Mz[Am2]   MN[Am2]  \
         0    230  CF AA pyrrhotite-5  0.000130  0.000063 -0.000029  0.000130
         1    231  CF AA pyrrhotite-5  0.000148  0.000007 -0.000051  0.000148
         2    232  CF AA pyrrhotite-5  0.000148  0.000007 -0.000051  0.000148
         3    233  CF AA pyrrhotite-5  0.000148  0.000007 -0.000051  0.000148
         4    234  CF AA pyrrhotite-5  0.000148  0.000007 -0.000051  0.000148

             ME[Am2]   MV[Am2]  Mtot[Am2]  Dec[deg]    ...     Ja/Jr  run#  \
         0  0.000063 -0.000029   0.000147  25.83010    ...         0   NaN
         1  0.000007 -0.000051   0.000156   2.89964    ...         0   NaN
         2  0.000007 -0.000051   0.000156   2.88449    ...         0   NaN
         3  0.000007 -0.000051   0.000156   2.87935    ...         0   NaN
         4  0.000007 -0.000051   0.000156   2.87825    ...         0   NaN

            Description  Meas_T[K]      Mode  Type  Mx_bsub[Am2]  My_bsub[Am2]  \
         0       289.42    290.745  DISCRETE   NaN      0.000131      0.000063
         1       290.98    291.961  DISCRETE   NaN      0.000149      0.000007
         2       291.24    292.114  DISCRETE   NaN      0.000149      0.000007
         3       291.33    292.170  DISCRETE   NaN      0.000149      0.000007
         4       291.40    292.230  DISCRETE   NaN      0.000149      0.000007

            Mz_bsub[Am2]  Mtotal_bsub[Am2]
         0     -0.000037          0.000150
         1     -0.000062          0.000162
         2     -0.000062          0.000161
         3     -0.000062          0.000161
```

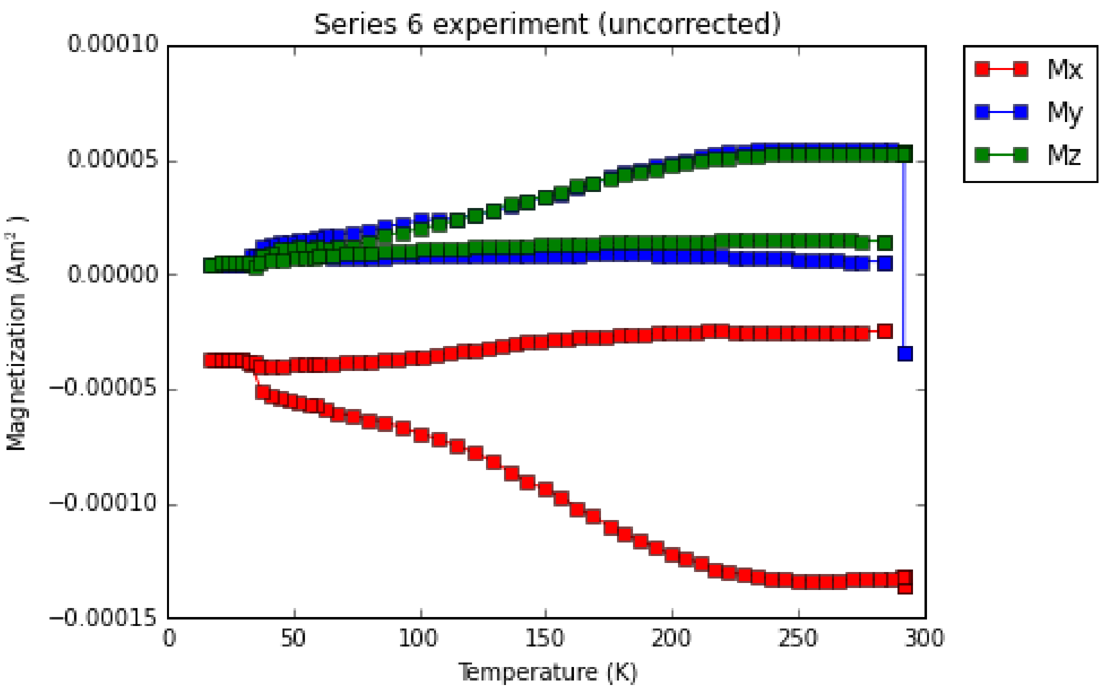
```
4     -0.000062          0.000161

[5 rows x 40 columns]
```

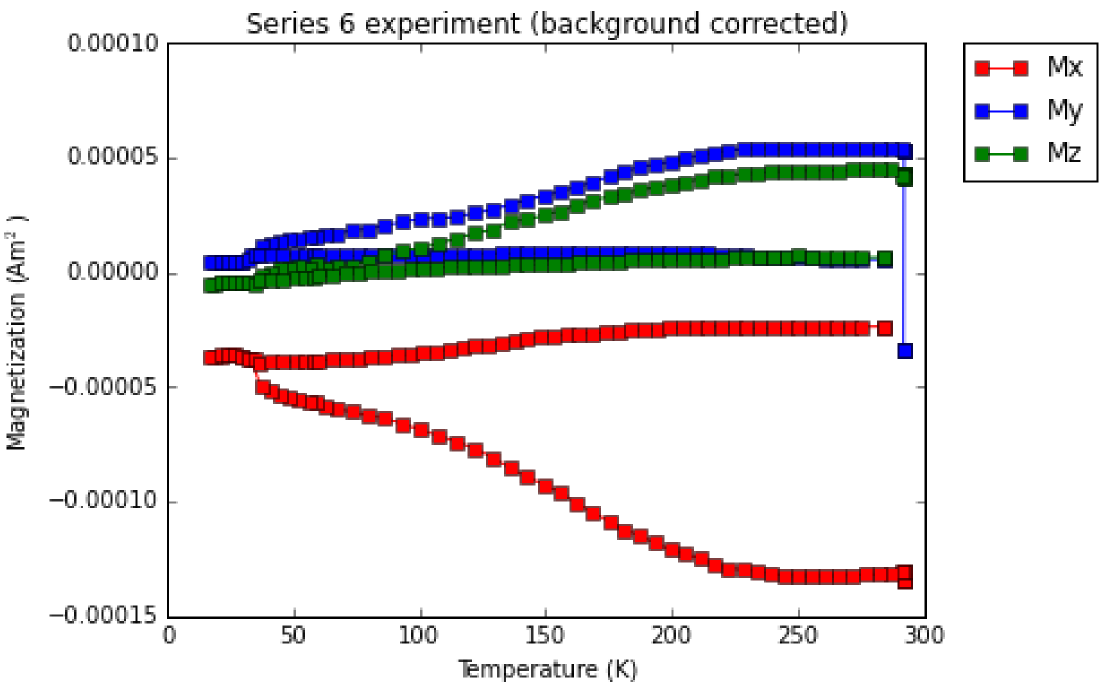
In [42]:
```
plt.figure(figsize=(6,10),dpi=160)
plt.subplot(211)
plt.plot(pyrrhotite_data_series5['Meas_T[K]'], pyrrhotite_data_series5['Mx[Am2]'], 'rs-',
         label='Mx')
plt.plot(pyrrhotite_data_series5['Meas_T[K]'], pyrrhotite_data_series5['My[Am2]'], 'bs-',
         label='My')
plt.plot(pyrrhotite_data_series5['Meas_T[K]'], pyrrhotite_data_series5['Mz[Am2]'], 'gs-',
         label='Mz')
plt.ylabel('Magnetization (Am$^2$)')
plt.xlabel('Temperature (K)')
plt.legend(bbox_to_anchor=(1.05, 1), loc=2, borderaxespad=0.)
plt.title('Series 5 experiment (uncorrected)')
plt.subplot(212)
plt.plot(pyrrhotite_data_series5['Meas_T[K]'], pyrrhotite_data_series5['Mx_bsub[Am2]'], 'rs-',
         label='Mx')
plt.plot(pyrrhotite_data_series5['Meas_T[K]'], pyrrhotite_data_series5['My_bsub[Am2]'], 'bs-',
         label='My')
plt.plot(pyrrhotite_data_series5['Meas_T[K]'], pyrrhotite_data_series5['Mz_bsub[Am2]'], 'gs-',
         label='Mz')
plt.ylabel('Magnetization (Am$^2$)')
plt.xlabel('Temperature (K)')
plt.legend(bbox_to_anchor=(1.05, 1), loc=2, borderaxespad=0.)
plt.title('Series 5 experiment (background corrected)')
plt.show()
```



In [43]:
```
plt.figure(figsize=(6,10),dpi=160)
plt.subplot(211)
plt.plot(pyrrhotite_data_series6['Meas_T[K]'], pyrrhotite_data_series6['Mx[Am2]'], 'rs-',
         label='Mx')
plt.plot(pyrrhotite_data_series6['Meas_T[K]'], pyrrhotite_data_series6['My[Am2]'], 'bs-',
         label='My')
plt.plot(pyrrhotite_data_series6['Meas_T[K]'], pyrrhotite_data_series6['Mz[Am2]'], 'gs-',
```

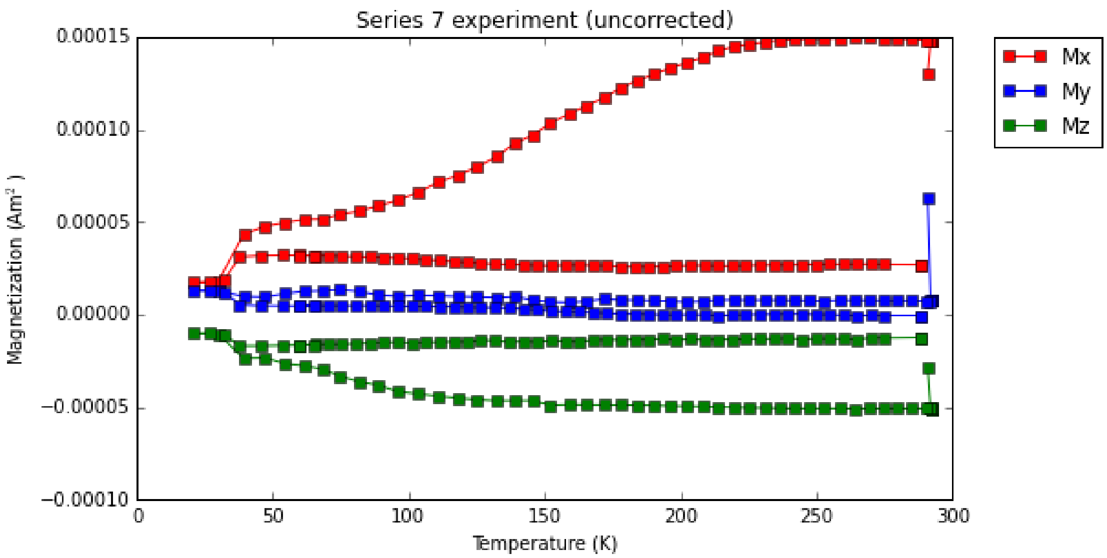
```
        label='Mz')
plt.ylabel('Magnetization (Am$^2$)')
plt.xlabel('Temperature (K)')
plt.legend(bbox_to_anchor=(1.05, 1), loc=2, borderaxespad=0.)
plt.title('Series 6 experiment (uncorrected)')
plt.subplot(212)
plt.plot(pyrrhotite_data_series6['Meas_T[K]'], pyrrhotite_data_series6['Mx_bsub[Am2]'], 'rs-',
        label='Mx')
plt.plot(pyrrhotite_data_series6['Meas_T[K]'], pyrrhotite_data_series6['My_bsub[Am2]'], 'bs-',
        label='My')
plt.plot(pyrrhotite_data_series6['Meas_T[K]'], pyrrhotite_data_series6['Mz_bsub[Am2]'], 'gs-',
        label='Mz')
plt.ylabel('Magnetization (Am$^2$)')
plt.xlabel('Temperature (K)')
plt.legend(bbox_to_anchor=(1.05, 1), loc=2, borderaxespad=0.)
plt.title('Series 6 experiment (background corrected)')
plt.show()
```

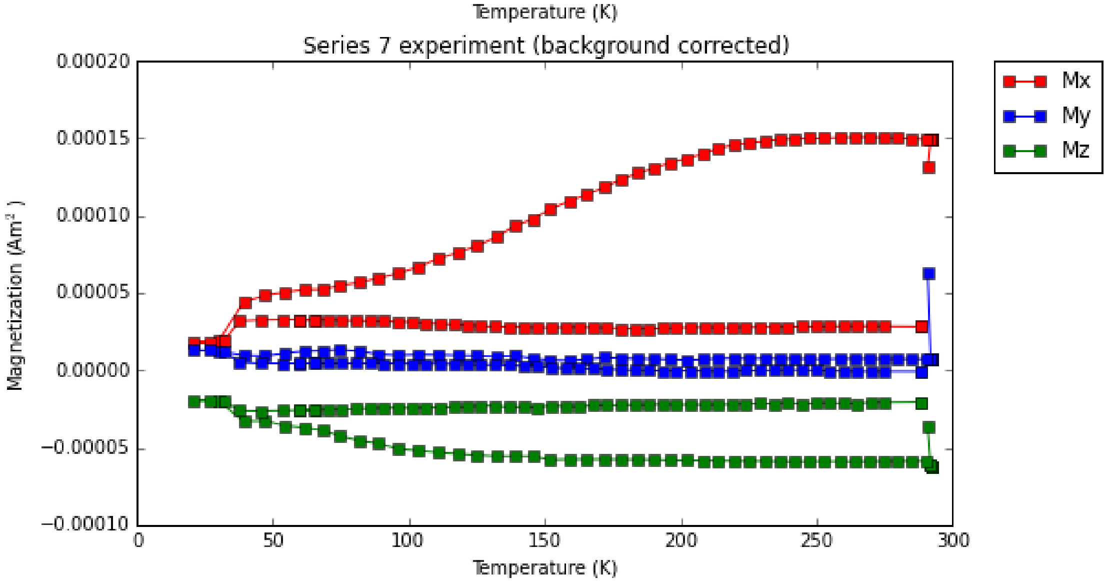




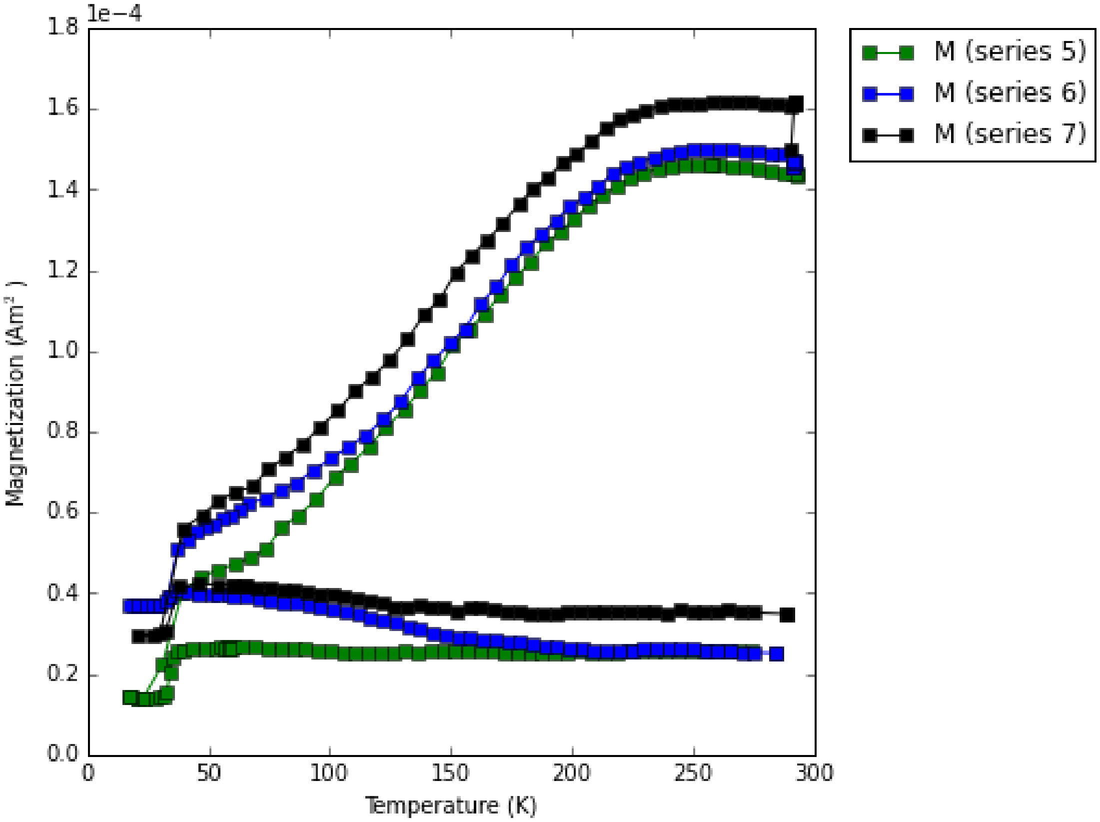
In [44]:
```
plt.figure(figsize=(8,10),dpi=160)
plt.subplot(211)
plt.plot(pyrrhotite_data_series7['Meas_T[K]'], pyrrhotite_data_series7['Mx[Am2]'], 'rs-',
         label='Mx')
plt.plot(pyrrhotite_data_series7['Meas_T[K]'], pyrrhotite_data_series7['My[Am2]'], 'bs-',
         label='My')
plt.plot(pyrrhotite_data_series7['Meas_T[K]'], pyrrhotite_data_series7['Mz[Am2]'], 'gs-',
```

```
         label='Mz')
plt.ylabel('Magnetization (Am$^2$)')
plt.xlabel('Temperature (K)')
plt.legend(bbox_to_anchor=(1.05, 1), loc=2, borderaxespad=0.)
plt.title('Series 7 experiment (uncorrected)')
plt.subplot(212)
plt.plot(pyrrhotite_data_series7['Meas_T[K]'], pyrrhotite_data_series7['Mx_bsub[Am2]'], 'rs-',
         label='Mx')
plt.plot(pyrrhotite_data_series7['Meas_T[K]'], pyrrhotite_data_series7['My_bsub[Am2]'], 'bs-',
         label='My')
plt.plot(pyrrhotite_data_series7['Meas_T[K]'], pyrrhotite_data_series7['Mz_bsub[Am2]'], 'gs-',
         label='Mz')
plt.ylabel('Magnetization (Am$^2$)')
plt.xlabel('Temperature (K)')
plt.legend(bbox_to_anchor=(1.05, 1), loc=2, borderaxespad=0.)
plt.title('Series 7 experiment (background corrected)')
plt.show()
```





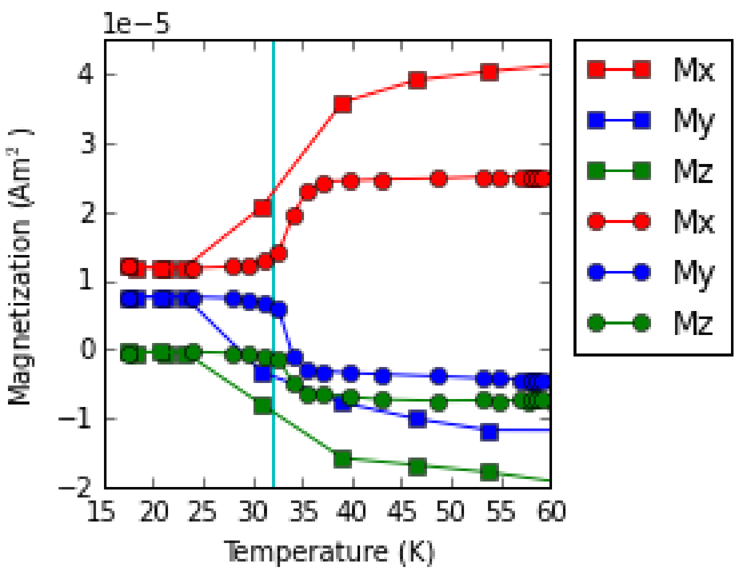
```
In [45]: plt.figure(figsize=(6,6),dpi=160)
         plt.plot(pyrrhotite_data_series5['Meas_T[K]'], pyrrhotite_data_series5['Mtotal_bsub[Am2]'], 'g
                  label='M (series 5)')
         plt.plot(pyrrhotite_data_series6['Meas_T[K]'], pyrrhotite_data_series6['Mtotal_bsub[Am2]'], 'b
                  label='M (series 6)')
         plt.plot(pyrrhotite_data_series7['Meas_T[K]'], pyrrhotite_data_series7['Mtotal_bsub[Am2]'], 'k
                  label='M (series 7)')
         plt.legend(bbox_to_anchor=(1.05, 1), loc=2, borderaxespad=0.)
         plt.ticklabel_format(style='sci', scilimits=(0,0), axis='y')
         plt.ylabel('Magnetization (Am$^2$)')
         plt.xlabel('Temperature (K)')
         plt.savefig('code_output/pyrrhotite_totalM_allseries.pdf')
         plt.show()
```



In each of the experiments the Besnus transition is prominent. Let's make a plot that zooms in the transition to highlight this aspect of the datasets. The series 5 warming data has a lot of points across the transition.

```
In [46]: plt.figure(figsize=(3,3),dpi=160)
         plt.plot(pyrrhotite_data_series5['Meas_T[K]'][:52], pyrrhotite_data_series5['Mx_bsub[Am2]'][:5
                  'rs-', label='Mx')
         plt.plot(pyrrhotite_data_series5['Meas_T[K]'][:52], pyrrhotite_data_series5['My_bsub[Am2]'][:5
```

```
             'bs-', label='My')
    plt.plot(pyrrhotite_data_series5['Meas_T[K]'][:52], pyrrhotite_data_series5['Mz_bsub[Am2]'][:52
             'gs-', label='Mz')
    plt.plot(pyrrhotite_data_series5['Meas_T[K]'][52:], pyrrhotite_data_series5['Mx_bsub[Am2]'][52
             'ro-', label='Mx')
    plt.plot(pyrrhotite_data_series5['Meas_T[K]'][52:], pyrrhotite_data_series5['My_bsub[Am2]'][52
             'bo-', label='My')
    plt.plot(pyrrhotite_data_series5['Meas_T[K]'][52:], pyrrhotite_data_series5['Mz_bsub[Am2]'][52
             'go-', label='Mz')
    plt.vlines(32, -2e-5,4.5e-5, colors='c')
    plt.xlim(15,60)
    plt.ylim(-2e-5,4.5e-5)
    plt.ticklabel_format(style='sci', scilimits=(0,0), axis='y')
    plt.ylabel('Magnetization (Am$^2$)')
    plt.xlabel('Temperature (K)')
    plt.legend(bbox_to_anchor=(1.05, 1), loc=2, borderaxespad=0.)
    #plt.title('Series 5 experiment (background corrected)')
    plt.savefig('code_output/pyrrhotite_detail.pdf')
    plt.show()
```



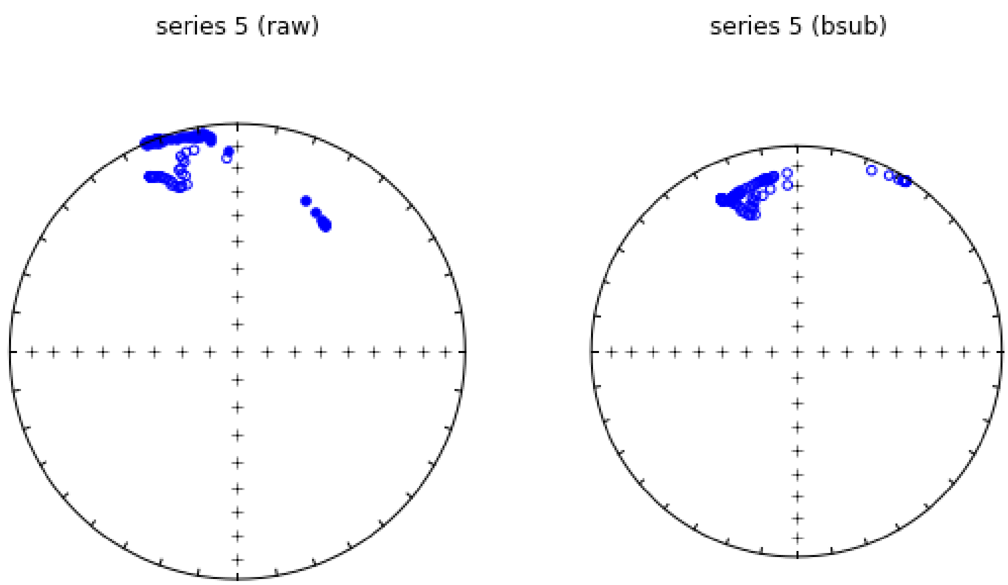
6.1 Directions of the pyrrhotite experiments

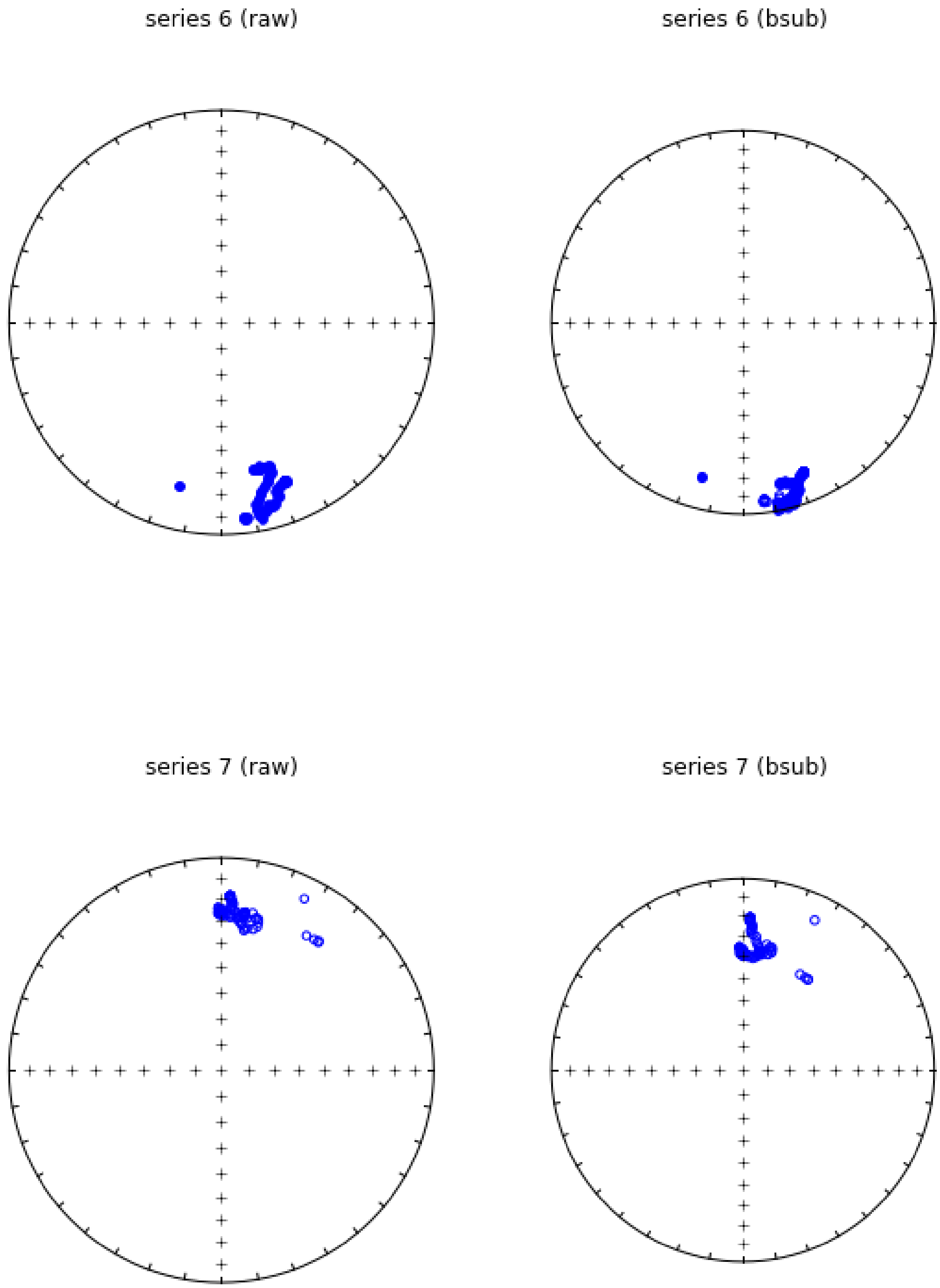
The directional data for these experiments is quite interesting. The pulse magnetizations were applied in different directions, but in each case the magnetization itself was acquired in the basal plane of the crystal.

```
In [47]: series5_cart=[]
         for n in range(len(pyrrhotite_data_series5)):
             series5_cart.append([pyrrhotite_data_series5['Mx[Am2]'][n],
                                  pyrrhotite_data_series5['My[Am2]'][n],
                                  pyrrhotite_data_series5['Mz[Am2]'][n]])
         series5_cart_bsub=[]
         for n in range(len(pyrrhotite_data_series5)):
```

```
    series5_cart_bsub.append([pyrrhotite_data_series5['Mx_bsub[Am2]'][n],
                                pyrrhotite_data_series5['My_bsub[Am2]'][n],
                                pyrrhotite_data_series5['Mz_bsub[Am2]'][n]])

series5_DI=pmag.cart2dir(series5_cart)
series5_DI_bsub=pmag.cart2dir(series5_cart_bsub)

fignum=1
fig=plt.figure(figsize=(8,5),dpi=160)
plt.subplot(121)
pmagplotlib.plotNET(fignum)
IPmag.iplotDI(series5_DI,'b')
plt.title('series 5 (raw)')

plt.subplot(122)
pmagplotlib.plotNET(fignum)
IPmag.iplotDI(series5_DI_bsub,'b')
plt.title('series 5 (bsub)')
plt.show()

series6_cart=[]
for n in range(len(pyrrhotite_data_series6)):
    series6_cart.append([pyrrhotite_data_series6['Mx[Am2]'][n],
                                pyrrhotite_data_series6['My[Am2]'][n],
                                pyrrhotite_data_series6['Mz[Am2]'][n]])
series6_cart_bsub=[]
for n in range(len(pyrrhotite_data_series6)):
    series6_cart_bsub.append([pyrrhotite_data_series6['Mx_bsub[Am2]'][n],
                                pyrrhotite_data_series6['My_bsub[Am2]'][n],
                                pyrrhotite_data_series6['Mz_bsub[Am2]'][n]])

series6_DI=pmag.cart2dir(series6_cart)
series6_DI_bsub=pmag.cart2dir(series6_cart_bsub)

fignum=2
fig=plt.figure(figsize=(8,5),dpi=160)
plt.subplot(121)
pmagplotlib.plotNET(fignum)
IPmag.iplotDI(series6_DI,'b')
plt.title('series 6 (raw)')

plt.subplot(122)
pmagplotlib.plotNET(fignum)
IPmag.iplotDI(series6_DI_bsub,'b')
plt.title('series 6 (bsub)')
plt.show()

series7_cart=[]
for n in range(len(pyrrhotite_data_series7)):
    series7_cart.append([pyrrhotite_data_series7['Mx[Am2]'][n],
                                pyrrhotite_data_series7['My[Am2]'][n],
                                pyrrhotite_data_series7['Mz[Am2]'][n]])

series7_cart_bsub=[]
```

```
for n in range(len(pyrrhotite_data_series7)):
    series7_cart_bsub.append([pyrrhotite_data_series7['Mx_bsub[Am2]'][n],
                              pyrrhotite_data_series7['My_bsub[Am2]'][n],
                              pyrrhotite_data_series7['Mz_bsub[Am2]'][n]])

series7_DI=pmag.cart2dir(series7_cart)
series7_DI_bsub=pmag.cart2dir(series7_cart_bsub)

fignum=3
fig=plt.figure(figsize=(8,5),dpi=160)
plt.subplot(121)
pmagplotlib.plotNET(fignum)
IPmag.iplotDI(series7_DI,'b')
plt.title('series 7 (raw)')

plt.subplot(122)
pmagplotlib.plotNET(fignum)
IPmag.iplotDI(series7_DI_bsub,'b')
plt.title('series 7 (bsub)')
plt.show()
```

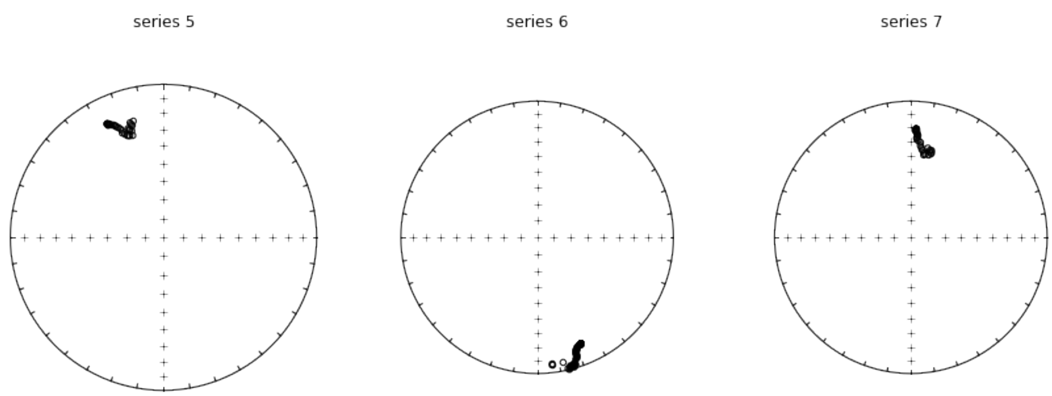




For the figure in the manuscript, we presented the background-corrected data upon cooling for each experiment. The code below generates the equal area plots for that figure.

```
In [48]: plt.figure(figsize=(12,5),dpi=160)
```

```
plt.subplot(131)
pmagplotlib.plotNET(fignum)
IPmag.iplotDI(series5_DI_bsub[1:45],'k')
#just plotting the points during cooling
plt.title('series 5')

plt.subplot(132)
pmagplotlib.plotNET(fignum)
IPmag.iplotDI(series6_DI_bsub[4:56],'k')
#just plotting the points during cooling
plt.title('series 6')

plt.subplot(133)
pmagplotlib.plotNET(fignum)
IPmag.iplotDI(series7_DI_bsub[1:50],'k')
plt.title('series 7')

plt.savefig('code_output/pyrrhotite_equal_area.pdf')
plt.show()
```



7 Umkondo Large Igneous Province sill experiments

7.1 Cold Finger Blank run on July 14, 2013

In [49]:
```
blank1_data_cooling = pd.read_table('../Data/Umkondo/Blank/20130714_blank_cooling.txt')
blank1_data_warming = pd.read_table('../Data/Umkondo/Blank/20130714_blank_warming.txt')
blank1_data_cooling.head()
```

Out[49]:
```
   measurement_T[K]       Mx[Am2]       My[Am2]       Mz[Am2]      M_N[Am2]  \
0             18.34 -1.339330e-08  6.227380e-09 -6.973380e-09 -1.339330e-08
1             26.43 -2.113220e-08  2.720220e-08 -9.012280e-09 -2.113220e-08
2             32.02 -2.133780e-08  3.355980e-08 -8.730760e-09 -2.133780e-08
3             37.88 -2.063060e-08  3.554850e-08 -8.082560e-09 -2.063060e-08
4             42.43 -1.917700e-08  3.565210e-08 -7.594180e-09 -1.917700e-08

    moment[Am2]
```

```
0    1.633370e-08
1    3.560550e-08
2    4.071600e-08
3    4.188850e-08
4    4.118860e-08
```

7.2 Cold Finger Blank run on July 24, 2013

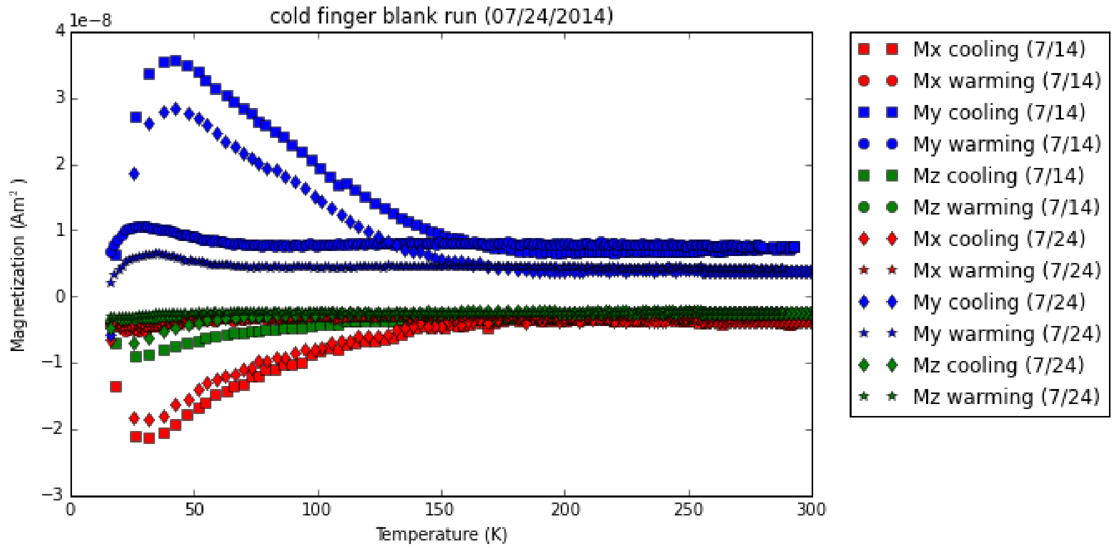
Import the blank run data into dataframes.

```
In [50]: blank2_data_cooling = pd.read_table('../Data/Umkondo/Blank/20130724_blank_cooling.txt')
         blank2_data_warming = pd.read_table('../Data/Umkondo/Blank/20130724_blank_warming.txt')
         blank2_data_warming.tail()
```

Out[50]:

	measurement_T[K]	Mx[Am2]	My[Am2]	Mz[Am2]	moment[Am2]
240	284.97	-2.893900e-09	4.405760e-09	-2.202820e-09	5.712950e-09
241	285.97	-2.974400e-09	4.076580e-09	-2.199280e-09	5.504760e-09
242	286.94	-3.071310e-09	4.289740e-09	-2.199440e-09	5.715980e-09
243	287.60	-2.690500e-09	4.263650e-09	-2.193600e-09	5.498130e-09
244	287.61	-3.253950e-09	4.218480e-09	-2.131440e-09	5.738190e-09

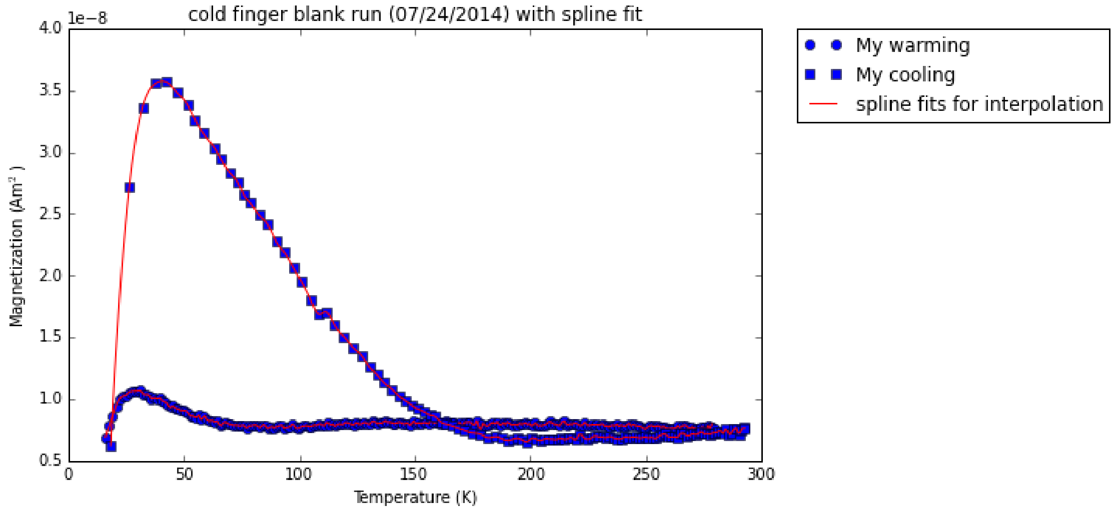
```
In [51]: plt.figure(figsize=(8,5),dpi=300)
         plt.plot(blank1_data_cooling['measurement_T[K]'], blank1_data_cooling['Mx[Am2]'], 'rs',
                  label='Mx cooling (7/14)')
         plt.plot(blank1_data_warming['measurement_T[K]'], blank1_data_warming['Mx[Am2]'], 'ro',
                  label='Mx warming (7/14)')
         plt.plot(blank1_data_cooling['measurement_T[K]'], blank1_data_cooling['My[Am2]'], 'bs',
                  label='My cooling (7/14)')
         plt.plot(blank1_data_warming['measurement_T[K]'], blank1_data_warming['My[Am2]'], 'bo',
                  label='My warming (7/14)')
         plt.plot(blank1_data_cooling['measurement_T[K]'], blank1_data_cooling['Mz[Am2]'], 'gs',
                  label='Mz cooling (7/14)')
         plt.plot(blank1_data_warming['measurement_T[K]'], blank1_data_warming['Mz[Am2]'], 'go',
                  label='Mz warming (7/14)')
         plt.plot(blank2_data_cooling['measurement_T[K]'], blank2_data_cooling['Mx[Am2]'], 'rd',
                  label='Mx cooling (7/24)')
         plt.plot(blank2_data_warming['measurement_T[K]'], blank2_data_warming['Mx[Am2]'], 'r*',
                  label='Mx warming (7/24)')
         plt.plot(blank2_data_cooling['measurement_T[K]'], blank2_data_cooling['My[Am2]'], 'bd',
                  label='My cooling (7/24)')
         plt.plot(blank2_data_warming['measurement_T[K]'], blank2_data_warming['My[Am2]'], 'b*',
                  label='My warming (7/24)')
         plt.plot(blank2_data_cooling['measurement_T[K]'], blank2_data_cooling['Mz[Am2]'], 'gd',
                  label='Mz cooling (7/24)')
         plt.plot(blank2_data_warming['measurement_T[K]'], blank2_data_warming['Mz[Am2]'], 'g*',
                  label='Mz warming (7/24)')

         plt.ylabel('Magnetization (Am$^2$)')
         plt.xlabel('Temperature (K)')
         plt.legend(bbox_to_anchor=(1.05, 1), loc=2, borderaxespad=0.)
         plt.title('cold finger blank run (07/24/2014)')
         plt.show()
```



The origin of this signal from the sample holder apparatus is currently unknown and will be investigated further in the future. The signal seems to remain broadly similar through repeated thermal cycling (compare the July 14, 2013 data to the July 24, 2013 data) so we will take the approach of subtracting the holder signal from the sample data. To do this holder subtraction, it is necessary to interpolate the holder signal at the temperatures for which sample data are collected. Here is an example of the spline interpolation of these data that we will use for this purpose. This spline interpolation is the one that is used in the background_sub() function defined above.

```
In [52]: x = blank1_data_warming['measurement_T[K]']
         y = blank1_data_warming['My[Am2]']
         spline = interpolate.splrep(x,y,s=0)
         xnew = np.linspace(blank1_data_warming['measurement_T[K]'].min(),
                            blank1_data_warming['measurement_T[K]'].max()-1, 300)
         ynew = interpolate.splev(xnew,spline,der=0)

         plt.figure(num=fignum,figsize=(8,5),dpi=300)
         plt.plot(x, y, 'bo',
                  label='My warming')
         plt.plot(xnew,ynew, 'r-')

         #For the interpolate function to work the x values (temperature) need to be ascending.
         #The blank1_data_cooling can be sorted so that temperatures are ascending
         blank1_data_cooling = blank1_data_cooling.sort(['measurement_T[K]'])

         x = blank1_data_cooling['measurement_T[K]']
         y = blank1_data_cooling['My[Am2]']
         tck = interpolate.splrep(x,y,s=0)
         xnew = np.linspace(blank1_data_cooling['measurement_T[K]'].min(),
                            blank1_data_cooling['measurement_T[K]'].max(), 300)
         ynew = interpolate.splev(xnew,tck,der=0)

         plt.plot(x, y, 'bs',
                  label='My cooling')
         plt.plot(xnew,ynew, 'r-',label='spline fits for interpolation')
```

```
plt.ylabel('Magnetization (Am$^2$)')
plt.xlabel('Temperature (K)')
plt.legend(bbox_to_anchor=(1.05, 1), loc=2, borderaxespad=0.)
plt.title('cold finger blank run (07/24/2014) with spline fit')
plt.show()
```



7.3 Experiments on PW10-7d

PW10 is a sill we refer to as the Rapitsane Sill from within the Umkondo Large Igneous Province in Botswana. Location: S 24.41968°, E 025.58463°. MPMS experiments and liquid nitrogen demagnetization revealed that this specimen lost a high percentage of its remanence upon cycling to and from low-temperature in low/near-zero field. The remanence removed during this low-temperature cycling is clearly an overprint on top of a primary

7.3.1 NRM demagnetization

```
In [53]: PW10_7a_demag = pd.read_csv('../Data/Umkondo/PW10/PW10-7a.csv')
         PW10_7a_demag
```

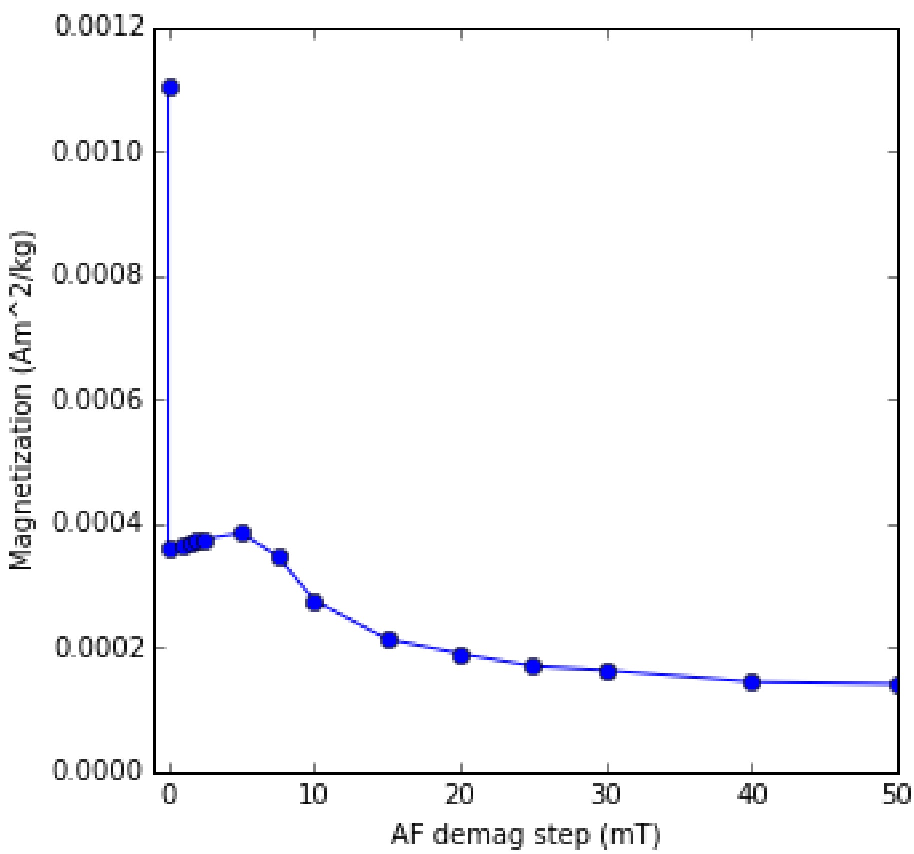
Out[53]:

	specimen	step	intensity	dec_geo	inc_geo	dec_spec	inc_spec
0	PW10-7a	0.0	0.001106	287.293	58.389400	131.3	49.4
1	PW10-7a	0.0	0.000362	205.501	25.299800	331.1	65.1
2	PW10-7a	1.0	0.000366	204.858	24.588300	330.4	64.2
3	PW10-7a	1.5	0.000369	204.310	23.822200	330.0	63.3
4	PW10-7a	2.0	0.000372	203.611	22.952500	329.4	62.3
5	PW10-7a	2.5	0.000375	202.734	21.649100	328.9	60.8
6	PW10-7a	5.0	0.000385	197.607	13.624400	326.2	51.5
7	PW10-7a	7.5	0.000348	192.869	6.610280	323.9	43.2
8	PW10-7a	10.0	0.000276	186.925	0.377430	320.2	35.1
9	PW10-7a	15.0	0.000214	184.698	-2.601010	319.3	31.4
10	PW10-7a	20.0	0.000190	187.394	-1.962070	321.9	33.2
11	PW10-7a	25.0	0.000170	189.228	-1.561390	323.7	34.3
12	PW10-7a	30.0	0.000163	189.053	-1.088220	323.3	34.6
13	PW10-7a	40.0	0.000145	186.617	4.399750	317.7	38.6
14	PW10-7a	50.0	0.000141	184.853	0.728249	317.8	34.5

```
In [54]: PW10_7a_datablock_geo=[]
         PW10_7a_datablock_spec=[]
         PW10_7a_DI_geo=[]
         PW10_7a_DI_spec=[]
         for n in range(0,len(PW10_7a_demag)):
             PW10_7a_datablock_geo.append([PW10_7a_demag['step'][n],
                                           PW10_7a_demag['dec_geo'][n],
                                           PW10_7a_demag['inc_geo'][n],
                                           PW10_7a_demag['intensity'][n]])
             PW10_7a_datablock_spec.append([PW10_7a_demag['step'][n],
                                           PW10_7a_demag['dec_spec'][n],
                                           PW10_7a_demag['inc_spec'][n],
                                           PW10_7a_demag['intensity'][n]])
             PW10_7a_DI_geo.append([PW10_7a_demag['dec_geo'][n],
                                    PW10_7a_demag['inc_geo'][n]])
             PW10_7a_DI_spec.append([PW10_7a_demag['dec_spec'][n],
                                     PW10_7a_demag['inc_spec'][n]])
```

Intensity plot

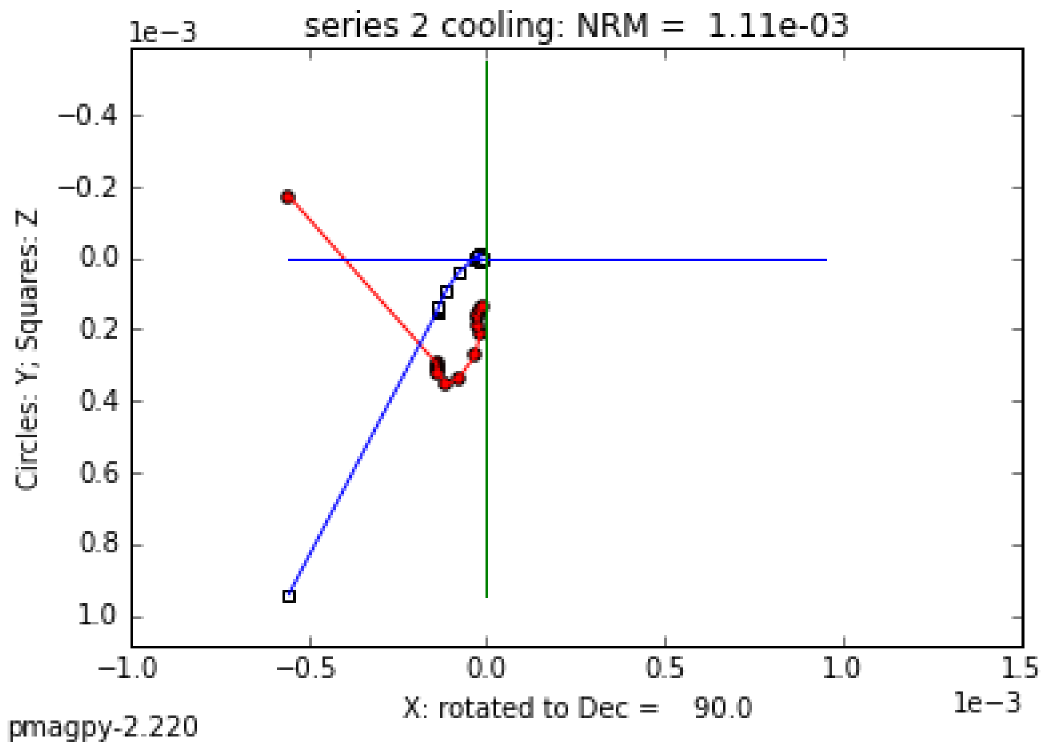
```
In [55]: plt.figure(figsize=(5,5))
         plt.plot(PW10_7a_demag['step'],PW10_7a_demag['intensity'],marker='o')
         plt.xlabel('AF demag step (mT)')
         plt.ylabel('Magnetization (Am^2/kg)')
         plt.xlim((-1,50))
         plt.show()
```

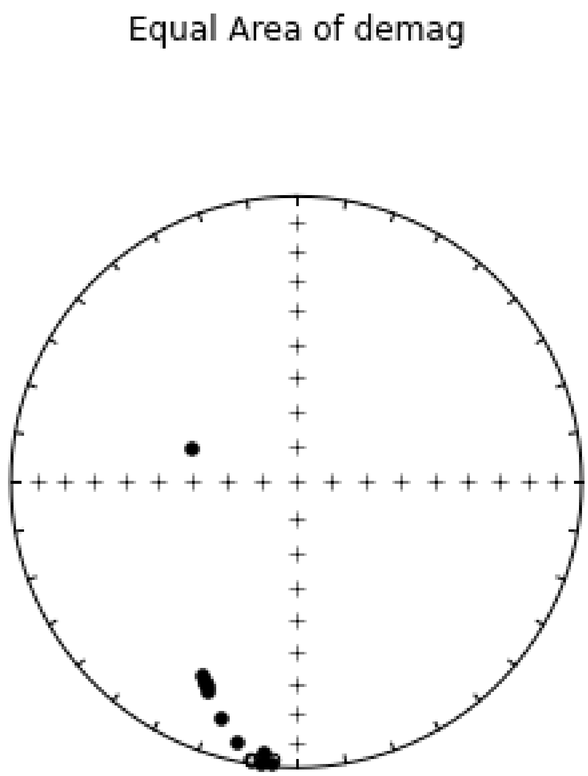


The large loss of remanence is associated with the 77K nitrogen bath.

Plots in geographic coordinates

In [56]:
```
#plot with pmagplotlib.plotZ(fignum,datablock,angle,s,norm)
pmagplotlib.plotZ(1,PW10_7a_datablock_geo,90,'series 2 cooling',0)
plt.ticklabel_format(style='sci', scilimits=(0,0), axis='y')
plt.ticklabel_format(style='sci', scilimits=(0,0), axis='x')
plt.show()

plt.figure(figsize=(5,5))
pmagplotlib.plotNET(1)
IPmag.iplotDI(PW10_7a_DI_geo)
plt.title('Equal Area of demag')
plt.show()
```

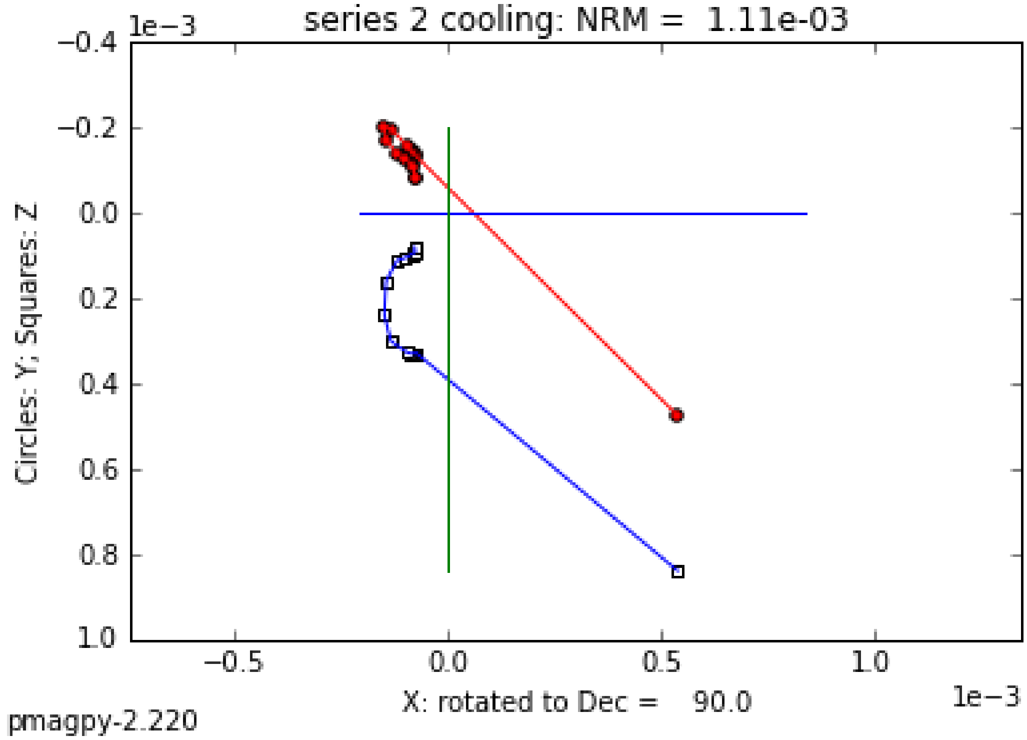




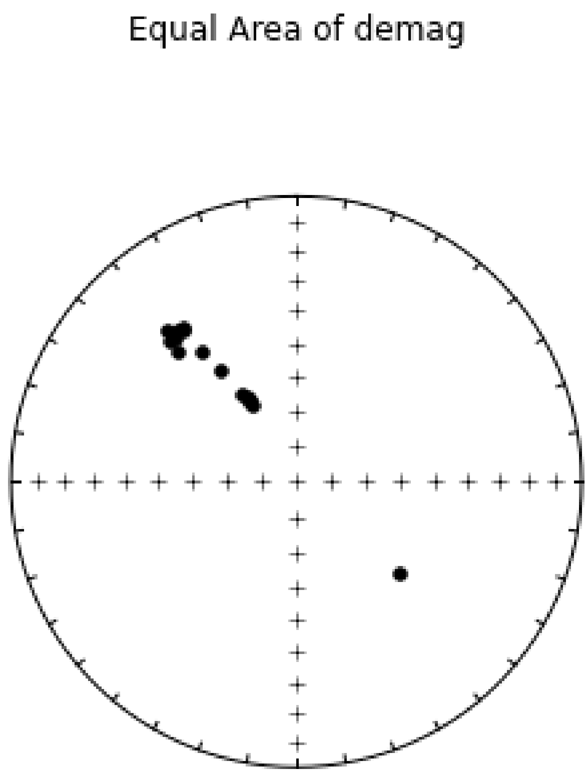
In the plots above, the large directional change and reduction in magnetization accompanies a low-temperature demagnetization step (i.e. 77 K nitrogen bath in a very low-field environment). Along with the following AF steps an overprint is removed that brings the data to the shallow southerly pointing vector which is consistent with other data from the ~1100 Ma Umkondo large igneous province.

Specimen coordinates These data plotted in specimen coordinates are more directly comparable to the data to acquired on another specimen from the same sample using the IRM-LTI.

```
In [57]: #plot with pmagplotlib.plotZ(fignum,datablock,angle,s,norm)
         pmagplotlib.plotZ(1,PW10_7a_datablock_spec,90,'series 2 cooling',0)
         plt.ticklabel_format(style='sci', scilimits=(0,0), axis='y')
         plt.ticklabel_format(style='sci', scilimits=(0,0), axis='x')
         plt.savefig('code_output/Umk_Pw10-7a_specimen_zplot.pdf')
         plt.show()

         plt.figure(figsize=(5,5))
         pmagplotlib.plotNET(1)
         IPmag.iplotDI(PW10_7a_DI_spec)
         plt.title('Equal Area of demag')
         plt.savefig('code_output/Umk_Pw10-7a_specimen_eqaplot.pdf')
         plt.show()
```



series 2 cooling: NRM = 1.11e-03
1e−3
−0.4
−0.2
0.0
0.2
0.4
0.6
0.8
1.0
Circles: Y; Squares: Z
−0.5
0.0
0.5
1.0
1e−3
X: rotated to Dec = 90.0
pmagpy-2.220



7.3.2 MPMS experiments on PW10-7d

```
In [58]: PW10_MPMS=pd.read_csv('../Data/Umkondo/PW10/PW10_7c_MPMS.csv',header=2)
         pd.set_option('display.max_columns', None)
         PW10_MPMS.head(5)
```

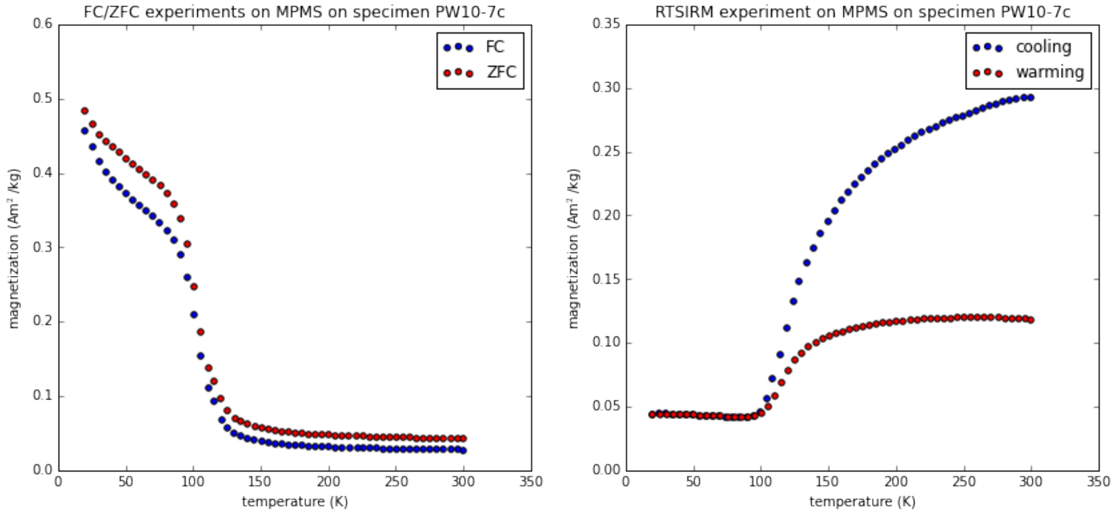
Out[58]:

	T [K]	Bapp [T]	M [Am2/kg]	reg fit	timestamp	Unnamed: 5	\
0	299.9879	2.5	2.885055	0.990173	2/5/2013 4:13:32 PM	NaN	
1	294.2503	2.5	2.899802	0.989840	2/5/2013 4:16:42 PM	NaN	
2	288.9702	2.5	2.914910	0.989691	2/5/2013 4:17:28 PM	NaN	
3	283.9853	2.5	2.931989	0.989543	2/5/2013 4:18:06 PM	NaN	
4	278.9876	2.5	2.951009	0.989169	2/5/2013 4:18:40 PM	NaN	

	T [K].1	Bapp [T].1	M [Am2/kg].1	reg fit.1	timestamp.1	\
0	19.99881	0	0.457038	0.990071	2/5/2013 5:27:50 PM	
1	25.59370	0	0.434746	0.989292	2/5/2013 5:29:09 PM	
2	30.62943	0	0.415489	0.989056	2/5/2013 5:30:10 PM	
3	35.51034	0	0.401149	0.988457	2/5/2013 5:31:10 PM	
4	40.58522	0	0.389925	0.988874	2/5/2013 5:32:11 PM	

```
   Unnamed: 11   T [K].2  Bapp [T].2  M [Am2/kg].2  reg fit.2  \
0          NaN  19.99765           0      0.483920   0.988106
1          NaN  25.55709           0      0.465696   0.987919
2          NaN  30.55221           0      0.451775   0.988061
3          NaN  35.59132           0      0.442285   0.987936
4          NaN  40.54948           0      0.434388   0.988107

           timestamp.2  Unnamed: 17   T [K].3  Bapp [T].3  M [Am2/kg].3  \
0  2/5/2013 7:43:34 PM          NaN  300.0001           0      0.292515
1  2/5/2013 7:44:54 PM          NaN  294.4174           0      0.292170
2  2/5/2013 7:45:55 PM          NaN  289.0140           0      0.291212
3  2/5/2013 7:46:57 PM          NaN  283.8555           0      0.290107
4  2/5/2013 7:47:56 PM          NaN  279.0740           0      0.288958

   reg fit.3          timestamp.3  Unnamed: 23   T [K].4  Bapp [T].4  \
0   0.989795  2/5/2013 8:53:56 PM          NaN  19.99720           0
1   0.989635  2/5/2013 8:56:51 PM          NaN  25.65808           0
2   0.989510  2/5/2013 8:57:42 PM          NaN  30.53962           0
3   0.989398  2/5/2013 8:58:22 PM          NaN  35.66172           0
4   0.989000  2/5/2013 8:58:58 PM          NaN  40.49764           0

   M [Am2/kg].4  reg fit.4           timestamp.4
0      0.044147   0.987200  2/5/2013 10:03:51 PM
1      0.044205   0.987814  2/5/2013 10:05:12 PM
2      0.044195   0.987583  2/5/2013 10:06:11 PM
3      0.044043   0.987072  2/5/2013 10:07:14 PM
4      0.043838   0.987979  2/5/2013 10:08:12 PM
```

In [59]:
```
fig=plt.figure(figsize=(14,6),dpi=160)
ax1 = fig.add_subplot(1, 2, 1)
ax2 = fig.add_subplot(1, 2, 2)
ax1.scatter(PW10_MPMS['T [K].1'],PW10_MPMS['M [Am2/kg].1'], c='b', label='FC')
ax1.scatter(PW10_MPMS['T [K].2'],PW10_MPMS['M [Am2/kg].2'], c='r', label='ZFC')
ax2.scatter(PW10_MPMS['T [K].3'],PW10_MPMS['M [Am2/kg].3'], c='b', label='cooling')
ax2.scatter(PW10_MPMS['T [K].4'],PW10_MPMS['M [Am2/kg].4'], c='r', label='warming')
ax1.set_xlabel('temperature (K)')
ax1.set_ylabel('magnetization (Am$^2$/kg)')
ax1.legend()
ax1.set_title('FC/ZFC experiments on MPMS on specimen PW10-7c')
ax2.set_xlabel('temperature (K)')
ax2.set_ylabel('magnetization (Am$^2$/kg)')
ax2.legend()
ax2.set_title('RTSIRM experiment on MPMS on specimen PW10-7c')
plt.savefig('code_output/PW10-7c_MPMS.svg')
plt.show()
```



7.3.3 IRM-LTI experiments on PW10-7d

Experiment on 07/21/2013 on specimen PW10-7d (measurement series 1 and 2): This experiment was designed to be low-temperature cycling of the specimens natural remanent magnetization (NRM).

Load the sample with arrow (down core z-axis) pointing out of SRM (old 2G at IRM) and make measurement (measurement series #1, measurement #1,2,3,4). The direction should be approx. the same as the measurement of the sister "a-series" specimen.

Twist the sample screw tight as is needed for running in low-temperature insert which results in sample being rotated about the z-axis (measurement series #1, measurement #5).

Cover the sample holder with the sapphire radiation shield and vacuum shroud ((measurement series #1, measurement #5) and then begin cooling. Measurements are made upon cooling (measurement series #2).

Once at minimum temperature (slightly below 20K) warm the probe back up progressively making measurements as it warms (measurement series #2).

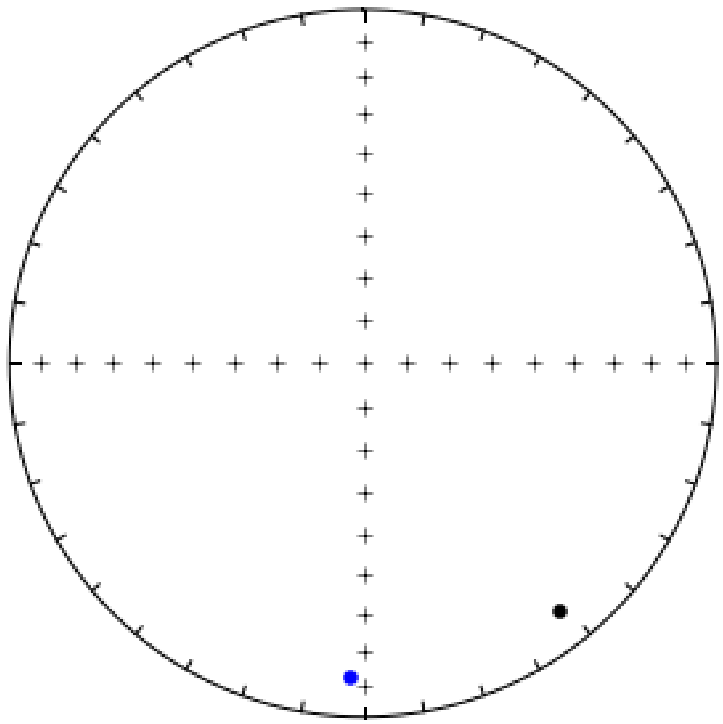
Import data file which has the format:
TEMPERATURE (K)
M_x [Am2]
M_y [Am2]
M_z [Am2]
M_total [Am2]
MEASUREMENT SERIES

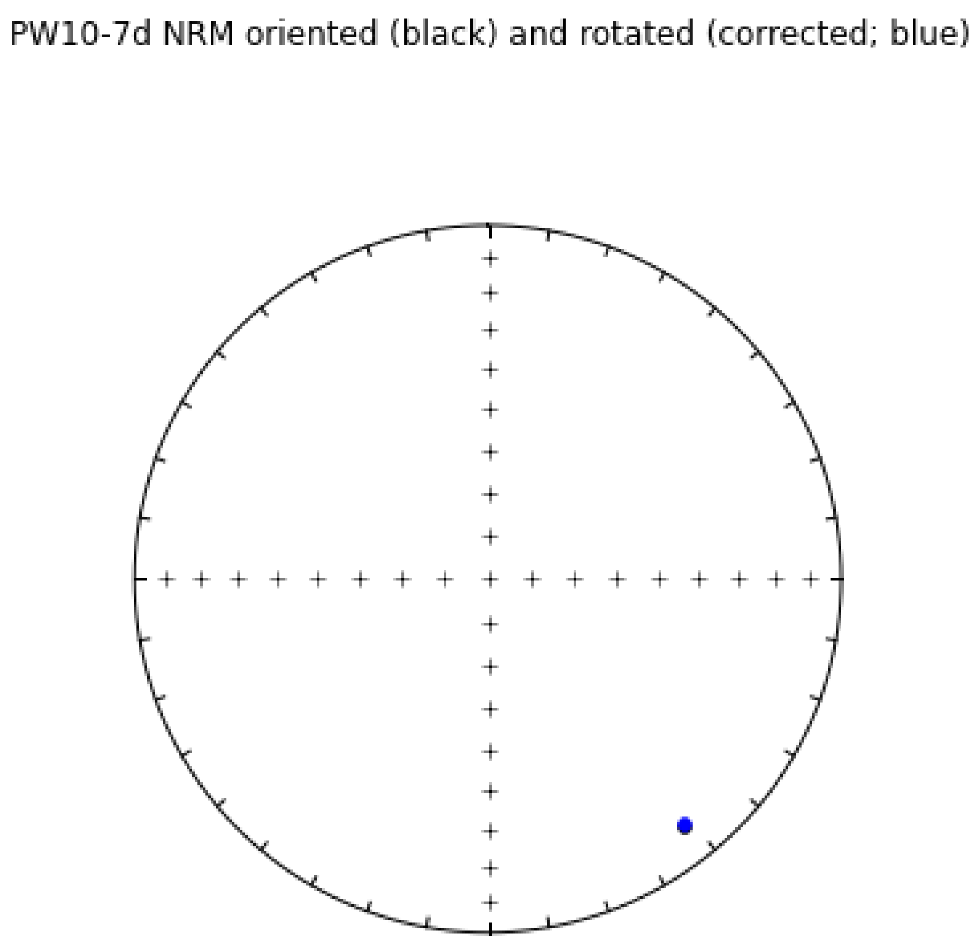
In [60]:
```
data_file='../Data/Umkondo/PW10/PW10-7d_rotation.txt'
data = np.genfromtxt(data_file, skip_header=1)

temp=data[:,0]
Mx=data[:,1]
My=data[:,2]
Mz=data[:,3]
Mtotal=data[:,4]
```

In [61]:
```
full_vector_oriented=[]
full_vector_rotated=[]

#data point 3 is oriented (remember python starts at 0)
```

```python
for n in range(3,4):
    Mx_full,My_full,Mz_full=Mx[n],My[n],Mz[n]
    full_vector_oriented.append([Mx_full,My_full,Mz_full])

#data point 4 is rotated about z (remember python starts at 0)
for n in range(4,5):
    Mx_full,My_full,Mz_full=Mx[n],My[n],Mz[n]
    full_vector_rotated.append([Mx_full,My_full,Mz_full])

oriented_directions=pmag.cart2dir(full_vector_oriented)
rotated_directions=pmag.cart2dir(full_vector_rotated)

#rotate the rotated directions about the z-axis to correspond to the oriented measurement
angle = 360 + oriented_directions.item(0) - rotated_directions.item(0)

x_prime = Mx[4]*np.cos(np.radians(angle)) - My[4]*np.sin(np.radians(angle))
y_prime = Mx[4]*np.sin(np.radians(angle)) + My[4]*np.cos(np.radians(angle))
z_prime = Mz[4]

full_vector_rotated_prime= [[x_prime,y_prime,z_prime]]
rotated_directions_prime=pmag.cart2dir(full_vector_rotated_prime)

#plot the oriented measurement and the rotated measurement
fignum = 1
plt.figure(num=fignum,figsize=(6,6),dpi=160)
pmagplotlib.plotNET(fignum)
IPmag.iplotDI(oriented_directions,'k')
IPmag.iplotDI(rotated_directions,'b')
plt.title('PW10-7d NRM oriented (black) and rotated (blue)');

#plot the oriented measurement and the corrected rotated measurement
fignum = 2
plt.figure(num=fignum,figsize=(6,6),dpi=160)
pmagplotlib.plotNET(fignum)
IPmag.iplotDI(oriented_directions,'k')
IPmag.iplotDI(rotated_directions_prime,'b')
plt.title('PW10-7d NRM oriented (black) and rotated (corrected; blue)');
```

PW10-7d NRM oriented (black) and rotated (blue)

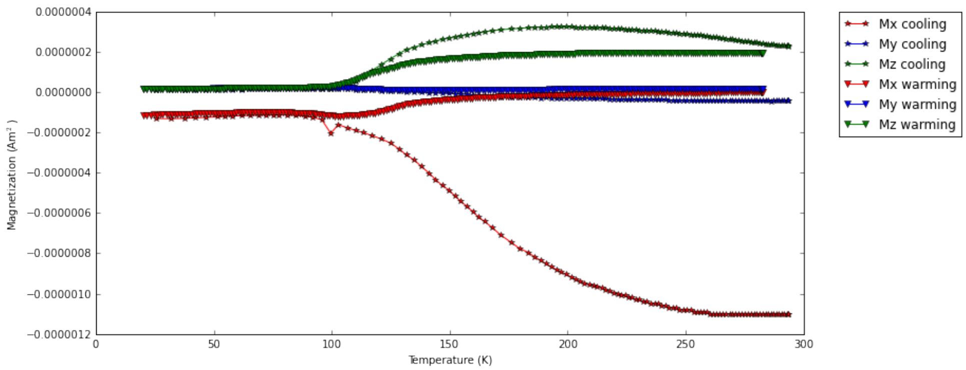


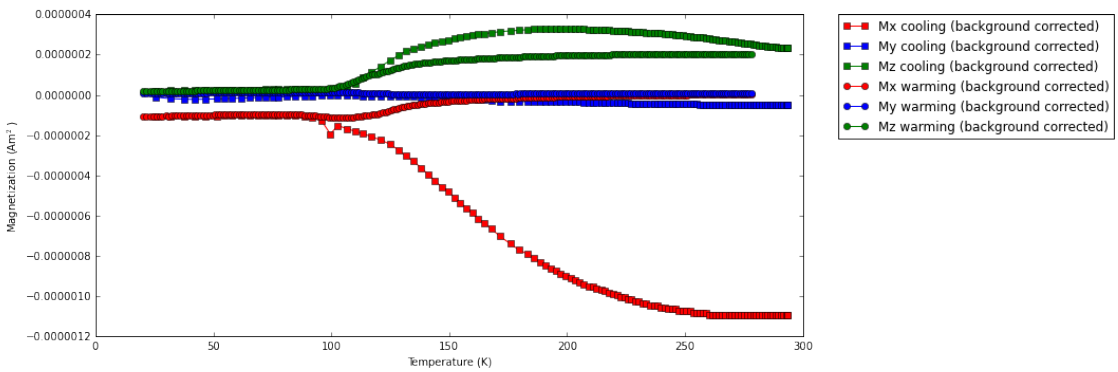



```
In [62]: data_file_cooling='../Data/Umkondo/PW10/PW10-7d_cooling.txt'
         data_cooling = np.genfromtxt(data_file_cooling, skip_header=1)

         temp_cooling=data_cooling[:,0]
         Mx_cooling=data_cooling[:,1]
         My_cooling=data_cooling[:,2]
         Mz_cooling=data_cooling[:,3]
         Mtotal_cooling=data_cooling[:,4]

         data_file_warming='../Data/Umkondo/PW10/PW10-7d_warming.txt'
         data_warming = np.genfromtxt(data_file_warming, skip_header=1)

         temp_warming=data_warming[:,0]
         Mx_warming=data_warming[:,1]
```

```
My_warming=data_warming[:,2]
Mz_warming=data_warming[:,3]
Mtotal_warming=data_warming[:,4]
```

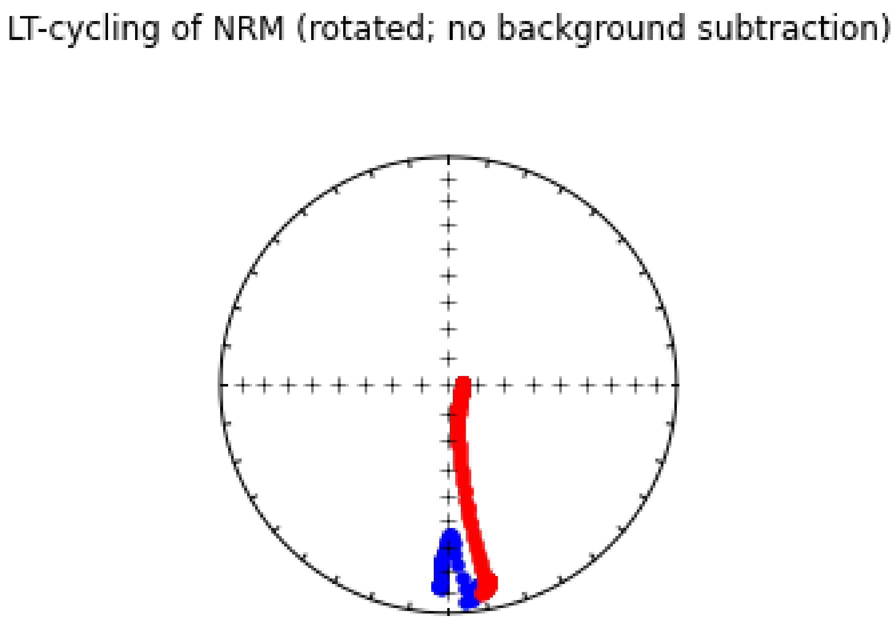
In [63]:
```
Mx_cooling_bsub = background_sub(blank1_data_cooling['Mx[Am2]'],blank1_data_cooling['measureme
                                 Mx_cooling,temp_cooling)

My_cooling_bsub = background_sub(blank1_data_cooling['My[Am2]'],blank1_data_cooling['measureme
                                 My_cooling,temp_cooling)

Mz_cooling_bsub = background_sub(blank1_data_cooling['Mz[Am2]'],blank1_data_cooling['measureme
                                 Mz_cooling,temp_cooling)

Mx_warming_bsub = background_sub(blank1_data_warming['Mx[Am2]'],blank1_data_warming['measureme
                                 Mx_warming[:-8],temp_warming[:-8])

My_warming_bsub = background_sub(blank1_data_warming['My[Am2]'],blank1_data_warming['measureme
                                 My_warming[:-8],temp_warming[:-8])

Mz_warming_bsub = background_sub(blank1_data_warming['Mz[Am2]'],blank1_data_warming['measureme
                                 Mz_warming[:-8],temp_warming[:-8])

fignum=1
plt.figure(num=fignum,figsize=(12,12),dpi=160)

ax=plt.subplot(211)
plt.plot(temp_cooling, Mx_cooling, 'r*-',label="Mx cooling")
plt.plot(temp_cooling, My_cooling, 'b*-',label="My cooling")
plt.plot(temp_cooling, Mz_cooling, 'g*-',label="Mz cooling")
plt.plot(temp_warming, Mx_warming, 'rv-',label="Mx warming")
plt.plot(temp_warming, My_warming, 'bv-',label="My warming")
plt.plot(temp_warming, Mz_warming, 'gv-',label="Mz warming")
plt.xlabel('Temperature (K)')
plt.ylabel('Magnetization (Am$^2$)')
plt.legend(bbox_to_anchor=(1.05, 1), loc=2, borderaxespad=0.)

ax=plt.subplot(212)
plt.plot(temp_cooling, Mx_cooling_bsub, 'rs-',
         label="Mx cooling (background corrected)")
plt.plot(temp_cooling, My_cooling_bsub, 'bs-',
         label="My cooling (background corrected)")
plt.plot(temp_cooling, Mz_cooling_bsub, 'gs-',
         label="Mz cooling (background corrected)")
plt.plot(temp_warming[:-8], Mx_warming_bsub, 'ro-',
         label="Mx warming (background corrected)")
plt.plot(temp_warming[:-8], My_warming_bsub, 'bo-',
         label="My warming (background corrected)")
plt.plot(temp_warming[:-8], Mz_warming_bsub, 'go-',
         label="Mz warming (background corrected)")
plt.xlabel('Temperature (K)')
plt.ylabel('Magnetization (Am$^2$)')
plt.legend(bbox_to_anchor=(1.05, 1), loc=2, borderaxespad=0.)
plt.show()
```

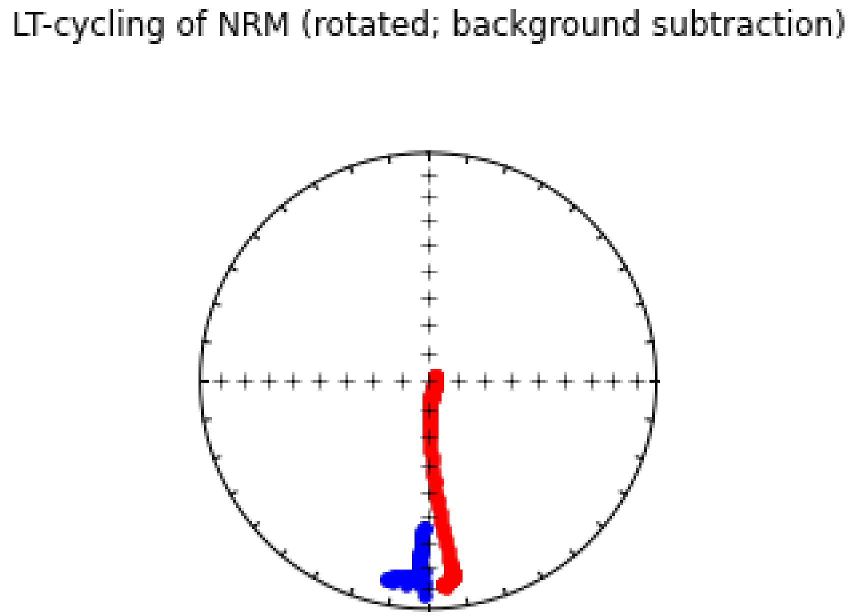




In [64]:
```
full_vector_cooling=[]
for n in range(0,len(temp_cooling)):
    full_vector_cooling.append([Mx_cooling[n],My_cooling[n],Mz_cooling[n]])
full_vector_warming=[]
for n in range(0,len(temp_warming)):
    full_vector_warming.append([Mx_warming[n],My_warming[n],Mz_warming[n]])

cooling_directions=pmag.cart2dir(full_vector_cooling)
warming_directions=pmag.cart2dir(full_vector_warming)

fignum=3
plt.figure(num=fignum,figsize=(4,4),dpi=160)
pmagplotlib.plotNET(fignum)
IPmag.iplotDI(cooling_directions,'b')
IPmag.iplotDI(warming_directions,'r')
plt.title('LT-cycling of NRM (rotated; no background subtraction)')
#plt.savefig('PW10-7d_3axisLTD_eqarea.svg')
plt.show()

full_vector_cooling=[]
for n in range(0,len(temp_cooling)):
    full_vector_cooling.append([Mx_cooling_bsub[n],My_cooling_bsub[n],Mz_cooling_bsub[n]])
full_vector_warming=[]
for n in range(0,len(Mx_warming_bsub)):
    full_vector_warming.append([Mx_warming_bsub[n],My_warming_bsub[n],Mz_warming_bsub[n]])

cooling_directions=pmag.cart2dir(full_vector_cooling)
```

```
warming_directions=pmag.cart2dir(full_vector_warming)

fignum=3
plt.figure(num=fignum,figsize=(4,4),dpi=160)
pmagplotlib.plotNET(fignum)
IPmag.iplotDI(cooling_directions,'b')
IPmag.iplotDI(warming_directions,'r')
plt.title('LT-cycling of NRM (rotated; background subtraction)')
#plt.savefig('PW10-7d_3axisLTD_eqarea.svg')
plt.show()
```

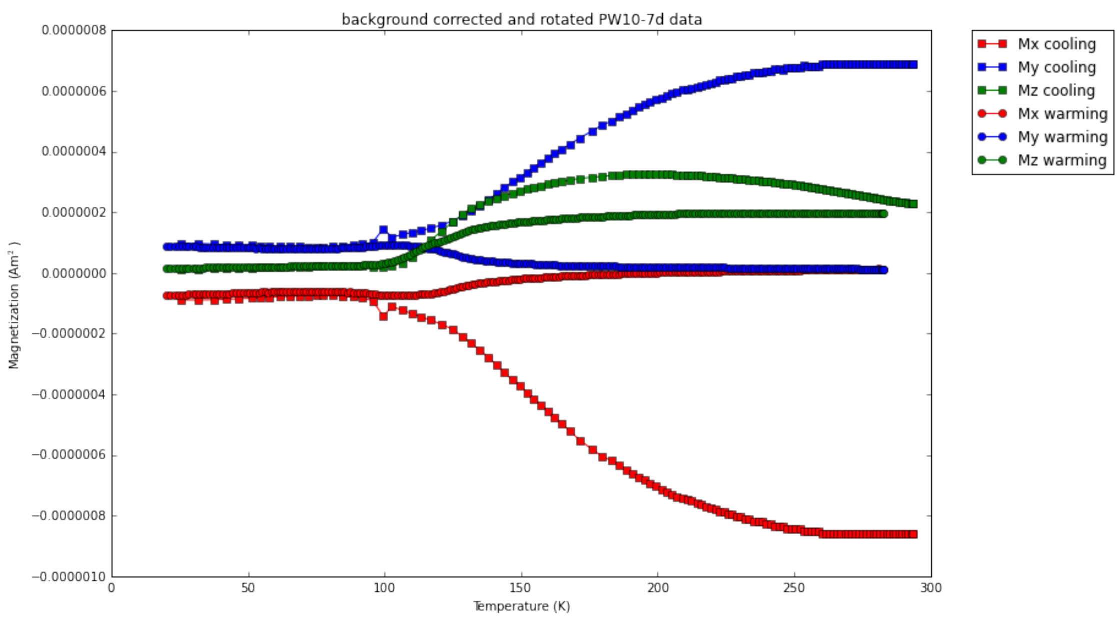




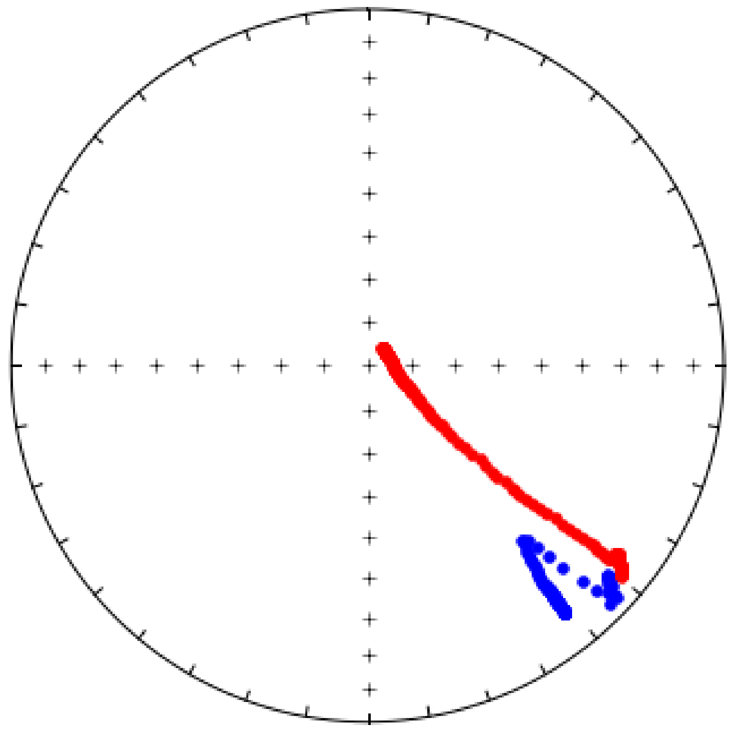
These plots show that the background subtraction is imperfect along the y-axis and is thereby adding an artifact to the data that is making it so that the end cooling values are not matching the start warming values. As can be seen in the data for the empty probe above, the y-axis has the highest magnetization in the blank probe runs with significant temperature dependent change. Given that the majority of the specimens directional change is in the z-axis and the z-axis data is minimally effected by the background subtraction, let's proceed with plotting the data that is not corrected for the holder, but is rotated back into specimen coordinates (e.g. Mz_cooling rather than Mz_cooling_bsub).

```
In [65]: Mx_cooling_prime = Mx_cooling*np.cos(np.radians(angle)) - My_cooling*np.sin(np.radians(angle))
         My_cooling_prime = Mx_cooling*np.sin(np.radians(angle)) + My_cooling*np.cos(np.radians(angle))
         Mz_cooling_prime = Mz_cooling
         full_vector_cooling=[]
         for n in range(0,len(temp_cooling)):
             full_vector_cooling.append([Mx_cooling_prime[n],My_cooling_prime[n],Mz_cooling_prime[n]])

         Mx_warming_prime = Mx_warming*np.cos(np.radians(angle)) - My_warming*np.sin(np.radians(angle))
         My_warming_prime = Mx_warming*np.sin(np.radians(angle)) + My_warming*np.cos(np.radians(angle))
         Mz_warming_prime = Mz_warming
         full_vector_warming=[]
         for n in range(0,len(temp_warming)):
             full_vector_warming.append([Mx_warming_prime[n],My_warming_prime[n],Mz_warming_prime[n]])

         fignum=2
         plt.figure(num=fignum,figsize=(12,8),dpi=160)
         plt.plot(temp_cooling, Mx_cooling_prime, 'rs-',label="Mx cooling")
         plt.plot(temp_cooling, My_cooling_prime, 'bs-',label="My cooling")
         plt.plot(temp_cooling, Mz_cooling_prime, 'gs-',label="Mz cooling")
```

```
plt.plot(temp_warming, Mx_warming_prime, 'ro-',label="Mx warming")
plt.plot(temp_warming, My_warming_prime, 'bo-',label="My warming")
plt.plot(temp_warming, Mz_warming_prime, 'go-',label="Mz warming")
plt.legend(bbox_to_anchor=(1.05, 1), loc=2, borderaxespad=0.)
plt.xlabel('Temperature (K)')
plt.ylabel('Magnetization (Am$^2$)')
plt.title('background corrected and rotated PW10-7d data')
plt.savefig('PW10-7d_3axisLTD.svg')

cooling_directions=pmag.cart2dir(full_vector_cooling)
warming_directions=pmag.cart2dir(full_vector_warming)

fignum=3
plt.figure(num=fignum,figsize=(7,7),dpi=160)
pmagplotlib.plotNET(fignum)
IPmag.iplotDI(cooling_directions,'b')
IPmag.iplotDI(warming_directions,'r')
plt.title('PW10-7d NRM upon cooling and warming (specimen coordinates)')
plt.savefig('code_output/PW10-7d_3axisLTD_eqarea.svg')
plt.show()
```

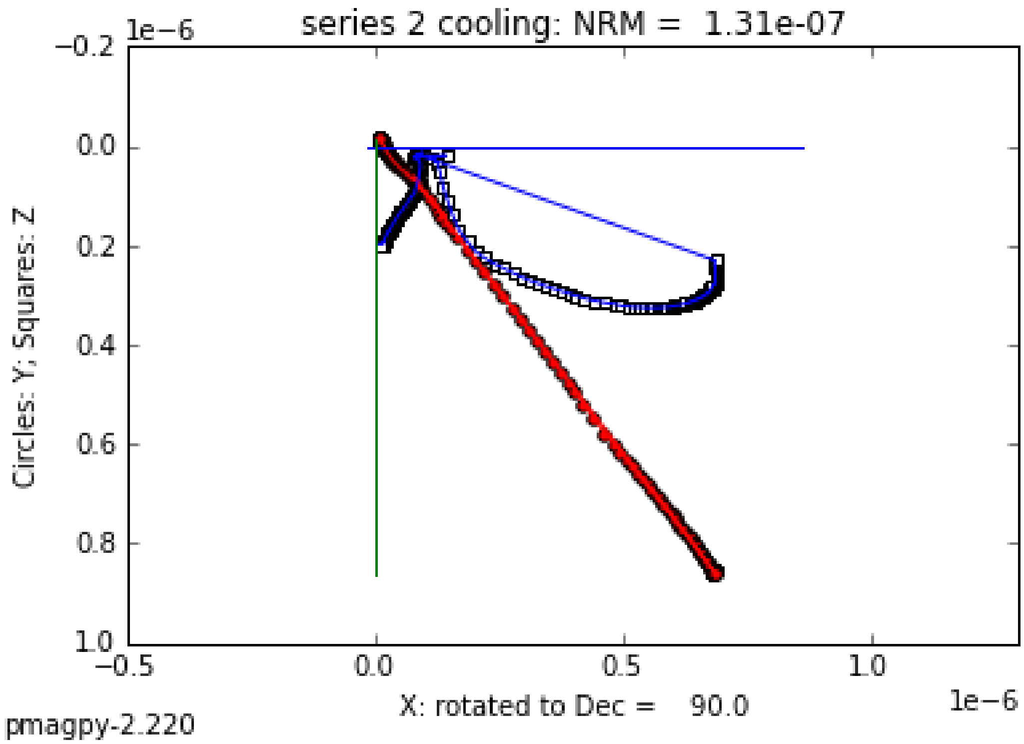


PW10-7d NRM upon cooling and warming (specimen coordinates)



```
In [66]: PW10_7d_datablock=[]

         for n in range(0,len(cooling_directions)):
             PW10_7d_datablock.append([temp_cooling[n],
                                       cooling_directions[n][0],
                                       cooling_directions[n][1],
                                       cooling_directions[n][2]])
         for n in range(0,len(warming_directions)):
             PW10_7d_datablock.append([temp_warming[n],
                                       warming_directions[n][0],
                                       warming_directions[n][1],
                                       warming_directions[n][2]])

         #plot with pmagplotlib.plotZ(fignum,datablock,angle,s,norm)
         pmagplotlib.plotZ(1,PW10_7d_datablock,90,'series 2 cooling',0)
```

```
plt.ticklabel_format(style='sci', scilimits=(0,0), axis='y')
plt.ticklabel_format(style='sci', scilimits=(0,0), axis='x')
plt.savefig('code_output/Umk_Pw10-7a_specimen_zplot.pdf')
plt.show()
```



7.4 PW15-4

This sample is from the an interior (~ 11 meters from margin) of an Umkondo Large Igneous Province diabase sill (the Mogatelwane 2 sill) and displayed a large loss in remanence associated with a liquid nitrogen treatment step that was applied during initial demagnetization of the NRM. Due to this behavior the sample was targeted for experiments on the low-temperature probe.

7.4.1 NRM demagnetization

In [67]:
```
PW15_4a_demag = pd.read_csv('../Data/Umkondo/PW15/PW15-4a.csv')
PW15_4a_demag
```

Out[67]:

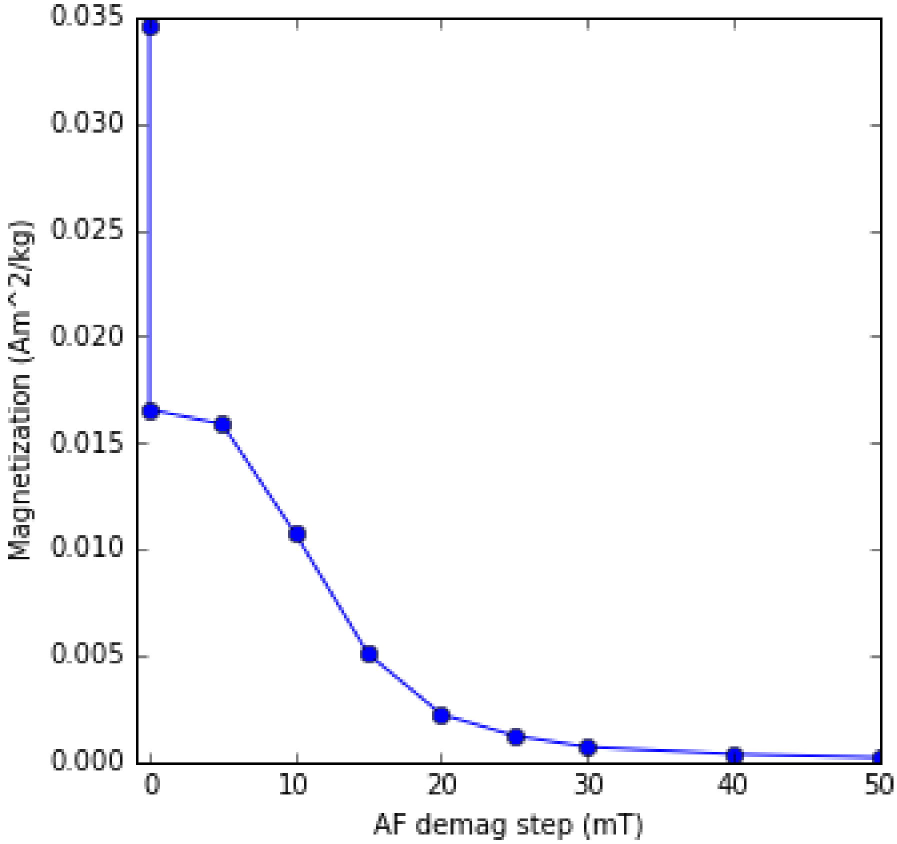
	specimen	step(mT)	intensity	dec_geo	inc_geo	dec_spec	inc_spec
0	PW15-4	0	0.034587	200.2	-7.8	354.3	72.1
1	PW15-4	0	0.016562	200.1	-9.1	354.2	70.8
2	PW15-4	5	0.015866	200.1	-8.8	354.3	71.1
3	PW15-4	10	0.010725	199.8	-8.1	352.9	71.7
4	PW15-4	15	0.005063	198.5	-9.9	349.8	69.8
5	PW15-4	20	0.002243	196.5	-12.2	346.0	67.2
6	PW15-4	25	0.001239	194.6	-11.6	341.1	67.2
7	PW15-4	30	0.000706	194.5	-11.6	340.7	67.1
8	PW15-4	40	0.000372	194.5	-12.4	341.4	66.4

9	PW15-4	50	0.000212	194.1	-13.3	341.2	65.4
10	PW15-4	60	0.000135	193.5	-14.0	340.5	64.6
11	PW15-4	70	0.000090	192.0	-12.6	336.1	65.3
12	PW15-4	80	0.000075	192.5	-15.6	339.6	62.7
13	PW15-4	90	0.000058	192.7	-11.5	336.4	66.6
14	PW15-4	100	0.000046	188.5	-10.8	326.9	65.3

In [68]:
```
PW15_4a_datablock_geo=[]
PW15_4a_datablock_spec=[]
PW15_4a_DI_geo=[]
PW15_4a_DI_spec=[]
for n in range(0,len(PW15_4a_demag)):
    PW15_4a_datablock_geo.append([PW15_4a_demag['step(mT)'][n],
                                  PW15_4a_demag['dec_geo'][n],
                                  PW15_4a_demag['inc_geo'][n],
                                  PW15_4a_demag['intensity'][n]])
    PW15_4a_datablock_spec.append([PW15_4a_demag['step(mT)'][n],
                                  PW15_4a_demag['dec_spec'][n],
                                  PW15_4a_demag['inc_spec'][n],
                                  PW15_4a_demag['intensity'][n]])
    PW15_4a_DI_geo.append([PW15_4a_demag['dec_geo'][n],
                           PW15_4a_demag['inc_geo'][n]])
    PW15_4a_DI_spec.append([PW15_4a_demag['dec_spec'][n],
                            PW15_4a_demag['inc_spec'][n]])
```

Intensity plot

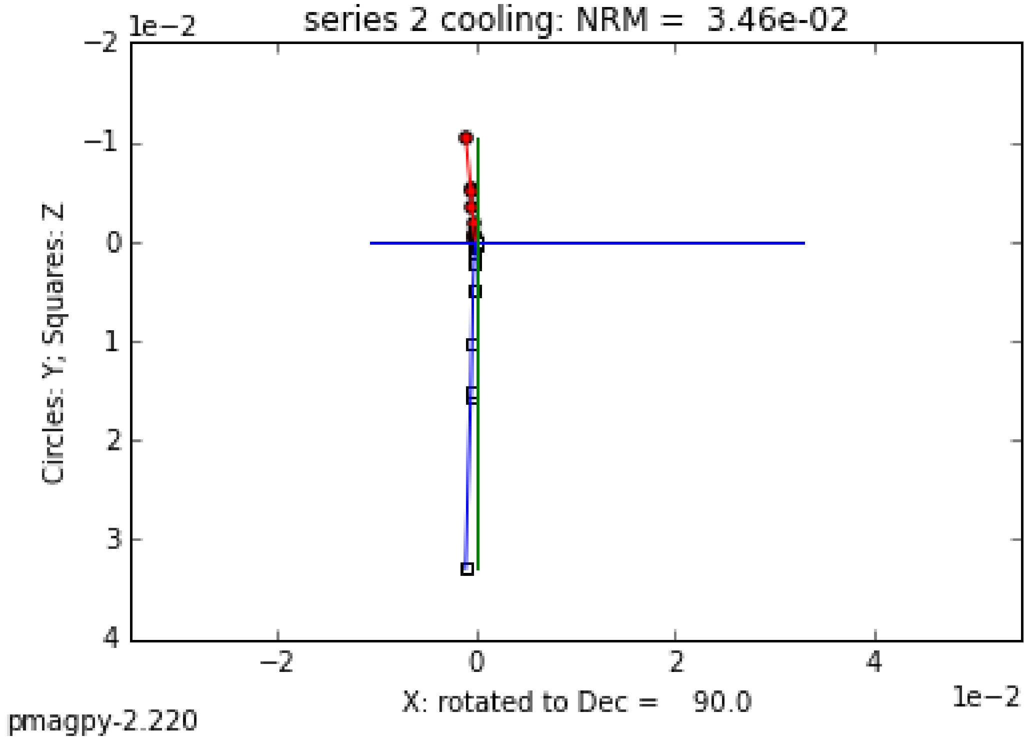
In [69]:
```
plt.figure(figsize=(5,5))
plt.plot(PW15_4a_demag['step(mT)'],PW15_4a_demag['intensity'],marker='o')
plt.xlabel('AF demag step (mT)')
plt.ylabel('Magnetization (Am^2/kg)')
plt.xlim((-1,50))
plt.savefig('code_output/PW15_4a_intensity.pdf')
plt.show()
```



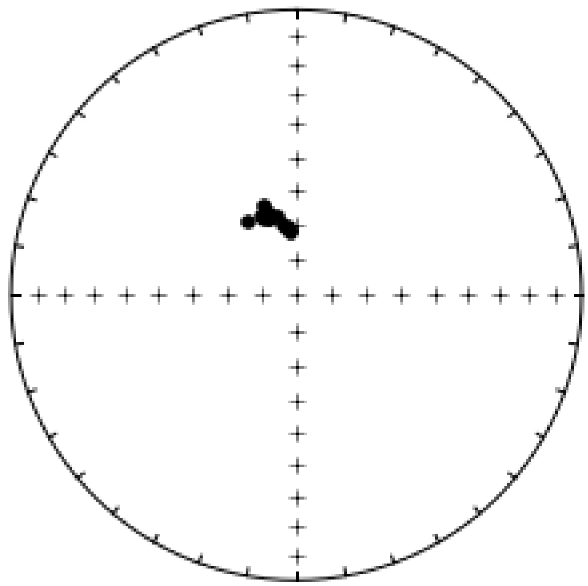
The large loss of remanence is associated with a low-temperature nitrogen bath in near-zero field.

Z-plot and equal area in specimen coordinates

In [70]:
```
#plot with pmagplotlib.plotZ(fignum,datablock,angle,s,norm)
pmagplotlib.plotZ(1,PW15_4a_datablock_spec,90,'series 2 cooling',0)
plt.ticklabel_format(style='sci', scilimits=(0,0), axis='y')
plt.ticklabel_format(style='sci', scilimits=(0,0), axis='x')
plt.savefig('code_output/PW15_4a_specimen_zplot.pdf')
plt.show()

plt.figure(figsize=(5,5))
pmagplotlib.plotNET(1)
IPmag.iplotDI(PW15_4a_DI_spec)
plt.title('Equal Area of demag')
plt.savefig('code_output/PW15_4a_specimen_eqaplot.pdf')
plt.show()
```


series 2 cooling: NRM = 3.46e-02
1e−2
−2
−1
0
1
2
3
4
Circles: Y; Squares: Z
−2
0
2
4
1e−2
X: rotated to Dec = 90.0
pmagpy-2.220

Equal Area of demag



The experiments conducted on the samples were as follows.

Load the sample with arrow (down core z-axis) pointing out of SRM (old 2G at IRM) and make measurement (measurement series #1, measurement #1). The direction should be approx. the same as the measurement of the sister "a-series" specimen.

Twist the sample screw tight as is needed for running in low-temperature insert which results in sample being rotated about the z-axis (measurement series #1, measurement #2).

Cover the sample holder with the sapphire radiation shield and vacuum shroud and then being cooling. Measurements are made upon cooling (measurement series #2).

Once at minimum temperature (slightly below 20K) warm the probe back up progressively making measurements as it warms (measurement series #2).

Import data file which has the format:

TEMPERATURE (K)

M_x [Am2]

M_y [Am2]

M_z [Am2]

M_total [Am2]

MEASUREMENT SERIES

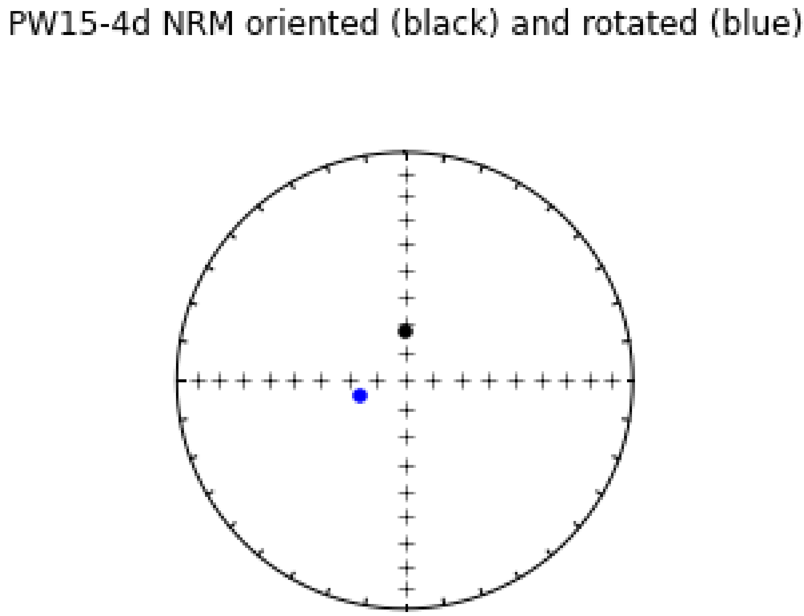
```
In [71]: PW15_data = pd.read_table('../Data/Umkondo/PW15/PW15-4d_LTI_experiments.txt')
         PW15_data.head()
```

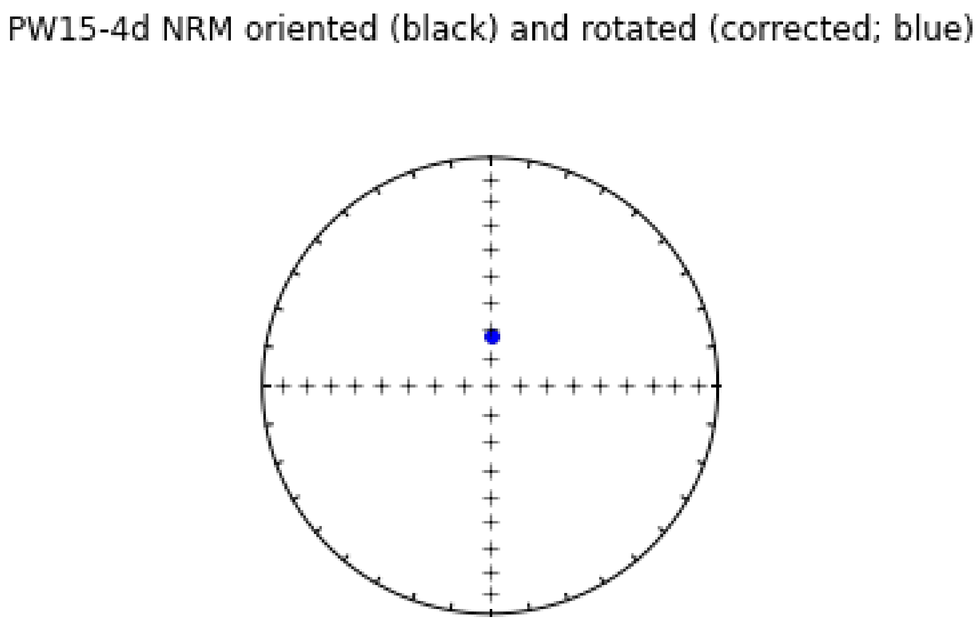
```
Out[71]:    measurement_T[K]   Mx[Am2]   My[Am2]   Mz[Am2]  moment[Am2]  \
        0             293.03  0.000007  0.000000  0.000024     0.000025
        1             292.90 -0.000002 -0.000007  0.000024     0.000025
        2             293.30 -0.000002 -0.000007  0.000024     0.000025
        3             293.59 -0.000002 -0.000007  0.000024     0.000025
        4             293.26 -0.000002 -0.000007  0.000024     0.000025

           Measurement_series
        0                   1
        1                   1
        2                   2
        3                   2
        4                   2
```

7.4.2 PW15-4d: Measurement series #1

```
In [72]: full_vector_oriented=[]
         full_vector_rotated=[]

         #data point 0 is oriented
         for n in range(0,1):
             full_vector_oriented.append([PW15_data['Mx[Am2]'][n],
                                          PW15_data['My[Am2]'][n],
                                          PW15_data['Mz[Am2]'][n]])

         #data point 1 is rotated about z
         for n in range(1,2):
             full_vector_rotated.append([PW15_data['Mx[Am2]'][n],
                                         PW15_data['My[Am2]'][n],
                                         PW15_data['Mz[Am2]'][n]])


         oriented_directions=pmag.cart2dir(full_vector_oriented)
         rotated_directions=pmag.cart2dir(full_vector_rotated)

         #rotate the rotated directions about the z-axis
         #to correspond to the oriented measurement
         angle = 360 + oriented_directions.item(0) - rotated_directions.item(0)

         x_prime = PW15_data['Mx[Am2]'][1]*np.cos(np.radians(angle)) - PW15_data['My[Am2]'][1]*np.sin(np
         y_prime = PW15_data['Mx[Am2]'][1]*np.sin(np.radians(angle)) + PW15_data['My[Am2]'][1]*np.cos(np
         z_prime = PW15_data['Mz[Am2]'][1]

         full_vector_rotated_prime= [[x_prime,y_prime,z_prime]]
         rotated_directions_prime=pmag.cart2dir(full_vector_rotated_prime)

         #plot the oriented measurement and the rotated measurement
         fignum = 1
         plt.figure(num=fignum,figsize=(4,4),dpi=160)
         pmagplotlib.plotNET(fignum)
         IPmag.iplotDI(oriented_directions,'k')
         IPmag.iplotDI(rotated_directions,'b')
         plt.title('PW15-4d NRM oriented (black) and rotated (blue)');
```

```python
#plot the oriented measurement and the corrected rotated measurement
fignum = 2
plt.figure(num=fignum,figsize=(4,4),dpi=160)
pmagplotlib.plotNET(fignum)
IPmag.iplotDI(oriented_directions,'k')
IPmag.iplotDI(rotated_directions_prime,'b')
plt.title('PW15-4d NRM oriented (black) and rotated (corrected; blue)');
```





7.4.3 PW15-4d: Measurement series #2

It will be more convenient to have the dataframe split into cooling and warming.

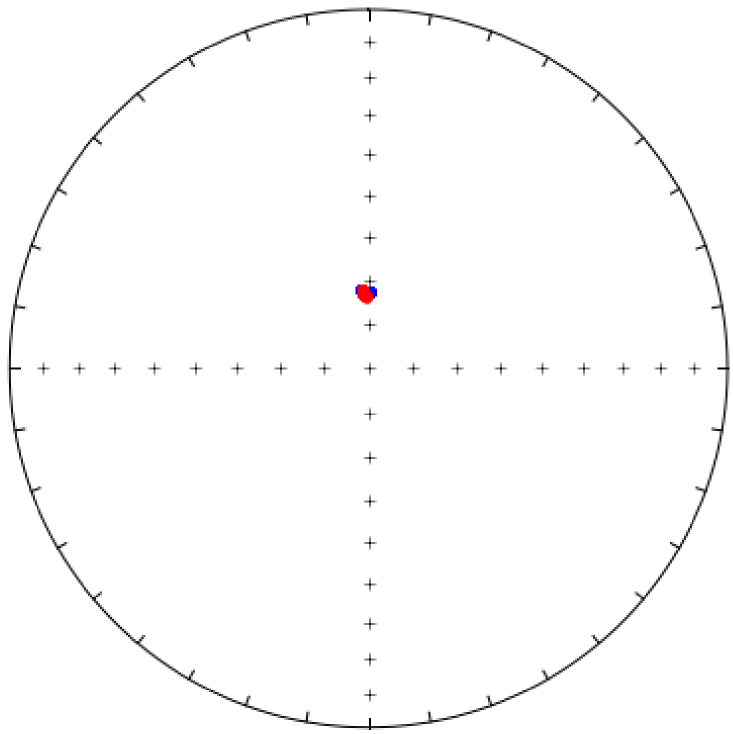
In [73]:
```
PW15_s2_cooling = PW15_data[2:121]
PW15_s2_cooling.reset_index(inplace='True')
PW15_s2_warming = PW15_data[129:374]
PW15_s2_warming.reset_index(inplace='True')

PW15_s2_warming.tail()
```

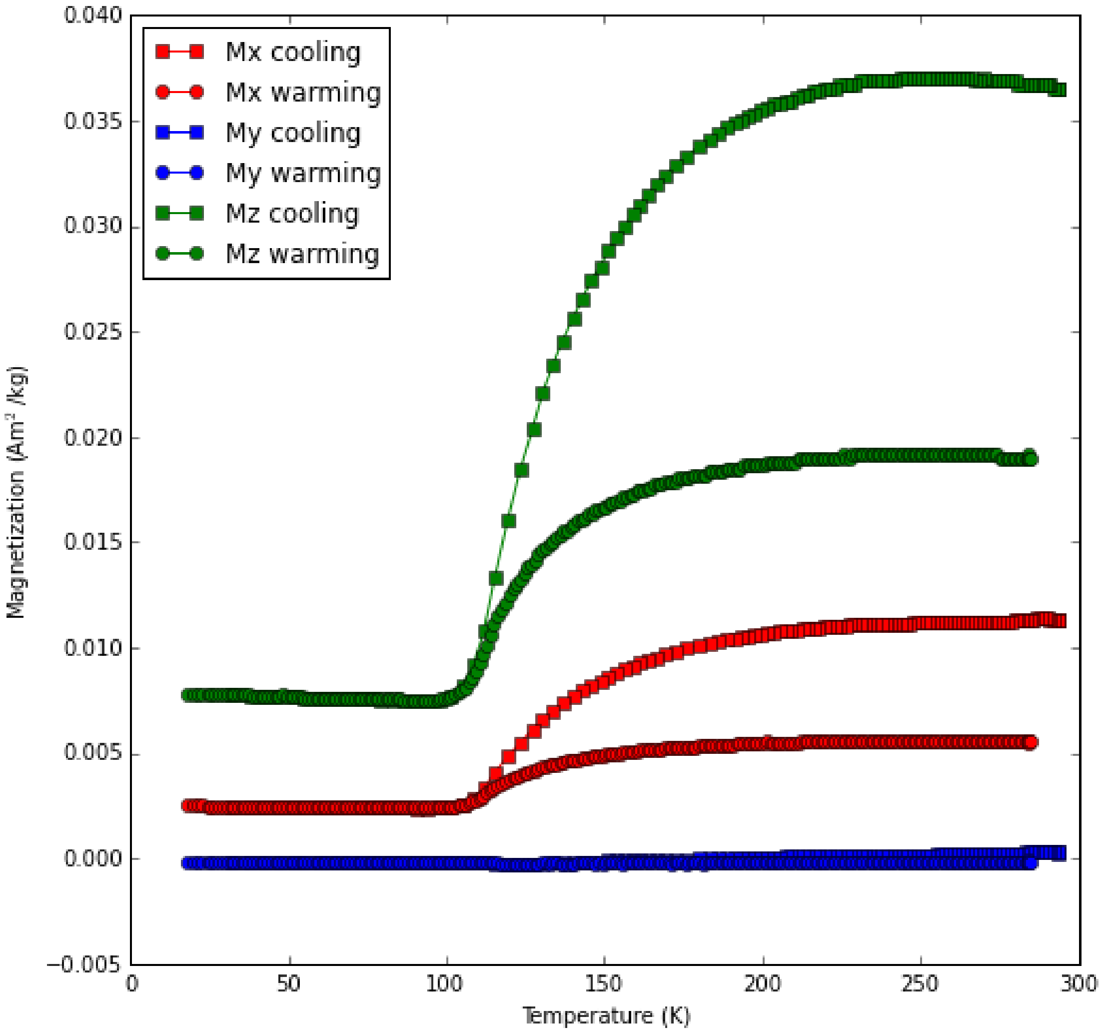
Out[73]:
```
     index  measurement_T[K]   Mx[Am2]   My[Am2]   Mz[Am2]  moment[Am2]  \
240    369            284.16 -0.000001 -0.000003  0.000012     0.000013
241    370            284.47 -0.000001 -0.000003  0.000012     0.000013
242    371            284.39 -0.000001 -0.000003  0.000012     0.000013
243    372            284.46 -0.000001 -0.000003  0.000012     0.000013
244    373            284.52 -0.000001 -0.000003  0.000012     0.000013

     Measurement_series
240                   2
241                   2
242                   2
243                   2
244                   2
```

The data need to be rotated into the oriented specimen coordinates. These rotated data will be called 'prime'.

```
In [74]: PW15_s2_cooling['Mx_prime[Am2]'] = PW15_s2_cooling['Mx[Am2]']*np.cos(np.radians(angle)) - PW15_
         PW15_s2_cooling['My_prime[Am2]'] = PW15_s2_cooling['Mx[Am2]']*np.sin(np.radians(angle)) + PW15_
         PW15_s2_cooling['Mz_prime[Am2]'] = PW15_s2_cooling['Mz[Am2]']

         full_vector_cooling_prime=[]
         for n in range(len(PW15_s2_cooling)):
             full_vector_cooling_prime.append([PW15_s2_cooling['Mx_prime[Am2]'][n],
                                               PW15_s2_cooling['My_prime[Am2]'][n],
                                               PW15_s2_cooling['Mz_prime[Am2]'][n]])

         PW15_s2_warming['Mx_prime[Am2]'] = PW15_s2_warming['Mx[Am2]']*np.cos(np.radians(angle)) - PW15_
         PW15_s2_warming['My_prime[Am2]'] = PW15_s2_warming['Mx[Am2]']*np.sin(np.radians(angle)) + PW15_
         PW15_s2_warming['Mz_prime[Am2]'] = PW15_s2_warming['Mz[Am2]']

         full_vector_warming_prime=[]
         for n in range(len(PW15_s2_warming)):
             full_vector_warming_prime.append([PW15_s2_warming['Mx_prime[Am2]'][n],
                                               PW15_s2_warming['My_prime[Am2]'][n],
                                               PW15_s2_warming['Mz_prime[Am2]'][n]])

In [75]: cooling_directions_prime=pmag.cart2dir(full_vector_cooling_prime)
         warming_directions_prime=pmag.cart2dir(full_vector_warming_prime)

         fignum=1
         plt.figure(num=fignum,figsize=(8,8),dpi=160) #size and resolution can be changed here
         pmagplotlib.plotNET(fignum)
         IPmag.iplotDI(cooling_directions_prime,'b')
         IPmag.iplotDI(warming_directions_prime,'r')
         plt.title('PW15-4d NRM upon cooling and warming (specimen coordinates)')
         plt.savefig('code_output/PW15-4d_equalarea.pdf')
         plt.show()

         #the specimen has a mass of .6483 g
         fignum=2
         plt.figure(num=fignum,figsize=(8,8),dpi=160)
         plt.plot(PW15_s2_cooling['measurement_T[K]'],
                  PW15_s2_cooling['Mx_prime[Am2]']/(.6483/1000), 'rs-')
         plt.plot(PW15_s2_warming['measurement_T[K]'],
                  PW15_s2_warming['Mx_prime[Am2]']/(.6483/1000), 'ro-')
         plt.plot(PW15_s2_cooling['measurement_T[K]'],
                  PW15_s2_cooling['My_prime[Am2]']/(.6483/1000), 'bs-')
         plt.plot(PW15_s2_warming['measurement_T[K]'],
                  PW15_s2_warming['My_prime[Am2]']/(.6483/1000), 'bo-')
         plt.plot(PW15_s2_cooling['measurement_T[K]'],
                  PW15_s2_cooling['Mz_prime[Am2]']/(.6483/1000), 'gs-')
         plt.plot(PW15_s2_warming['measurement_T[K]'],
                  PW15_s2_warming['Mz_prime[Am2]']/(.6483/1000), 'go-')
         plt.xlabel('Temperature (K)')
         plt.ylabel('Magnetization (Am$^2$/kg)')
         plt.legend(('Mx cooling','Mx warming','My cooling','My warming','Mz cooling','Mz warming'),loc=
         plt.savefig('code_output/PW15-4d_3axis.svg')
         plt.show()
```

PW15-4d NRM upon cooling and warming (specimen coordinates)





7.4.4 Experiment on 07/18/2013 on specimen PW15-4d:

This experiment was designed to impart an ARM to the sample and a perpendicular pARM (to low coercivities) to the sample in order to ascertain the behavior of the low-coercivity ARM and resolve directional change during low-temperature cycling.

Give the specimen a negative z-axis ARM (0.03 mT bias field in 200 mT AF field) and measure (measurement 1 in measurement series #3) (after the measurement the decision was made to increase the bias field in order to increase the moment)

Give the specimen a negative z-axis ARM (0.1 mT bias field in 200 mT AF field) and measure (measurement 2 in measurement series #3)

Give the specimen a negative x-axis ARM (0.1 mT bias field in 5 mT AF field) and measure (measurement 3 in measurement series #3) (after the measurement the decision was made to increase the of this pARM bias field in order to increase the moment)

Give the specimen a negative x-axis ARM (0.2 mT bias field in 5 mT AF field) and measure (measurement 4 in measurement series #3)

Tightening the sample holder for the cryogenic experiment requires rotating the sample an unknown amount about the z-axis (measurement 5 in measurement series #3)

Cover the sample holder with the sapphire radiation shield and vacuum shroud and then being cooling. Measurements are made upon cooling and subsequent warming (measurement series #4).

In [76]: PW15_data

Out[76]:

```
     measurement_T[K]       Mx[Am2]       My[Am2]   Mz[Am2]  moment[Am2]  \
0              293.03  7.470000e-06  1.580000e-07  0.000024     0.000025
1              292.90 -2.390000e-06 -6.910000e-06  0.000024     0.000025
2              293.30 -2.320000e-06 -6.950000e-06  0.000024     0.000025
3              293.59 -2.420000e-06 -6.950000e-06  0.000024     0.000025
4              293.26 -2.340000e-06 -6.960000e-06  0.000024     0.000025
5              292.23 -2.340000e-06 -6.970000e-06  0.000024     0.000025
6              291.18 -2.350000e-06 -6.980000e-06  0.000024     0.000025
7              290.43 -2.350000e-06 -6.990000e-06  0.000024     0.000025
8              289.33 -2.350000e-06 -6.990000e-06  0.000024     0.000025
9              288.09 -2.360000e-06 -7.000000e-06  0.000024     0.000025
10             286.95 -2.360000e-06 -6.980000e-06  0.000024     0.000025
11             285.80 -2.370000e-06 -6.970000e-06  0.000024     0.000025
12             284.68 -2.370000e-06 -6.950000e-06  0.000024     0.000025
13             283.48 -2.370000e-06 -6.930000e-06  0.000024     0.000025
14             282.29 -2.380000e-06 -6.920000e-06  0.000024     0.000025
15             281.06 -2.380000e-06 -6.920000e-06  0.000024     0.000025
16             279.86 -2.380000e-06 -6.910000e-06  0.000024     0.000025
17             278.63 -2.380000e-06 -6.900000e-06  0.000024     0.000025
18             277.38 -2.390000e-06 -6.890000e-06  0.000024     0.000025
19             276.16 -2.390000e-06 -6.890000e-06  0.000024     0.000025
20             274.92 -2.390000e-06 -6.880000e-06  0.000024     0.000025
21             273.62 -2.390000e-06 -6.870000e-06  0.000024     0.000025
22             272.35 -2.390000e-06 -6.860000e-06  0.000024     0.000025
23             270.99 -2.390000e-06 -6.860000e-06  0.000024     0.000025
24             269.75 -2.390000e-06 -6.860000e-06  0.000024     0.000025
25             268.46 -2.400000e-06 -6.850000e-06  0.000024     0.000025
26             267.11 -2.400000e-06 -6.850000e-06  0.000024     0.000025
27             265.85 -2.400000e-06 -6.850000e-06  0.000024     0.000025
28             264.43 -2.400000e-06 -6.850000e-06  0.000024     0.000025
29             263.13 -2.400000e-06 -6.840000e-06  0.000024     0.000025
..                ...           ...           ...       ...          ...
718            258.54 -6.470000e-08  3.050000e-08 -0.000000     0.000001
719            259.56 -6.500000e-08  3.040000e-08 -0.000000     0.000001
720            260.58 -6.510000e-08  3.030000e-08 -0.000000     0.000001
721            261.60 -6.430000e-08  3.040000e-08 -0.000000     0.000001
722            262.59 -6.490000e-08  3.030000e-08 -0.000000     0.000001
723            263.58 -6.440000e-08  3.030000e-08 -0.000000     0.000001
724            264.64 -6.430000e-08  3.040000e-08 -0.000000     0.000001
725            265.65 -6.420000e-08  3.020000e-08 -0.000000     0.000001
726            266.67 -6.480000e-08  3.030000e-08 -0.000000     0.000001
727            267.71 -6.470000e-08  3.030000e-08 -0.000000     0.000001
728            268.72 -6.450000e-08  3.020000e-08 -0.000000     0.000001
729            269.74 -6.420000e-08  3.020000e-08 -0.000000     0.000001
730            270.80 -6.470000e-08  3.020000e-08 -0.000000     0.000001
731            271.81 -6.440000e-08  3.040000e-08 -0.000000     0.000001
732            272.84 -6.430000e-08  3.020000e-08 -0.000000     0.000001
733            273.79 -6.430000e-08  3.030000e-08 -0.000000     0.000001
734            274.81 -6.460000e-08  3.030000e-08 -0.000000     0.000001
735            275.80 -6.400000e-08  3.040000e-08 -0.000000     0.000001
```

736	276.82	-6.440000e-08	3.050000e-08	-0.000000	0.000001
737	277.20	-6.470000e-08	3.030000e-08	-0.000000	0.000001
738	278.21	-6.410000e-08	3.030000e-08	-0.000000	0.000001
739	279.25	-6.450000e-08	3.040000e-08	-0.000000	0.000001
740	280.29	-6.400000e-08	3.040000e-08	-0.000000	0.000001
741	281.38	-6.420000e-08	3.040000e-08	-0.000000	0.000001
742	282.38	-6.500000e-08	2.770000e-08	-0.000000	0.000001
743	283.38	-6.470000e-08	3.020000e-08	-0.000000	0.000001
744	283.85	-6.440000e-08	3.040000e-08	-0.000000	0.000001
745	283.91	-6.440000e-08	3.040000e-08	-0.000000	0.000001
746	284.03	-6.470000e-08	3.040000e-08	-0.000000	0.000001
747	284.11	-6.450000e-08	3.030000e-08	-0.000000	0.000001

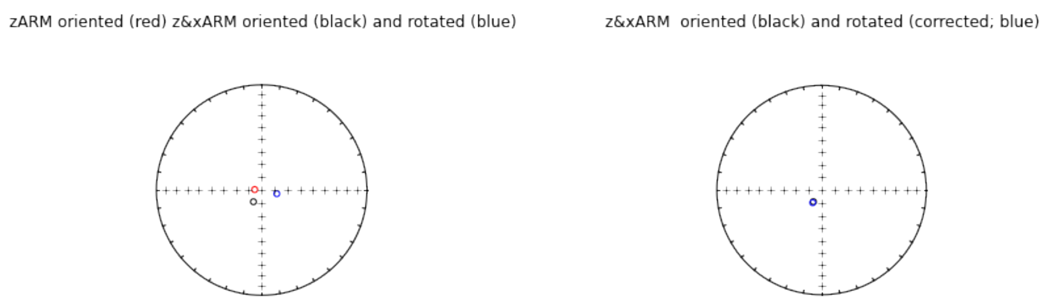
	Measurement_series
0	1
1	1
2	2
3	2
4	2
5	2
6	2
7	2
8	2
9	2
10	2
11	2
12	2
13	2
14	2
15	2
16	2
17	2
18	2
19	2
20	2
21	2
22	2
23	2
24	2
25	2
26	2
27	2
28	2
29	2
..	...
718	4
719	4
720	4
721	4
722	4
723	4
724	4
725	4
726	4

```
727                    4
728                    4
729                    4
730                    4
731                    4
732                    4
733                    4
734                    4
735                    4
736                    4
737                    4
738                    4
739                    4
740                    4
741                    4
742                    4
743                    4
744                    4
745                    4
746                    4
747                    4

[748 rows x 6 columns]
```

PW15-4d: Measurement series #3

In [77]:
```
zARM_oriented=[]
zARMxARM_oriented=[]
zARMxARM_rotated=[]

#negative z-axis ARM (0.1 mT bias field in 200 mT AF field)
for n in range(375,376):
    Mx_full=PW15_data['Mx[Am2]'][n]
    My_full=PW15_data['My[Am2]'][n]
    Mz_full=PW15_data['Mz[Am2]'][n]
    zARM_oriented.append([Mx_full,My_full,Mz_full])

#negative z-axis ARM (0.1 mT bias field in 200 mT AF field) + negative x-axis ARM (0.2 mT bias
for n in range(377,378):
    Mx_full=PW15_data['Mx[Am2]'][n]
    My_full=PW15_data['My[Am2]'][n]
    Mz_full=PW15_data['Mz[Am2]'][n]
    zARMxARM_oriented.append([Mx_full,My_full,Mz_full])

#negative z-axis ARM (0.1 mT bias field in 200 mT AF field) + negative x-axis ARM (0.2 mT bias
for n in range(378,379):
    Mx_full=PW15_data['Mx[Am2]'][n]
    My_full=PW15_data['My[Am2]'][n]
    Mz_full=PW15_data['Mz[Am2]'][n]
    zARMxARM_rotated.append([Mx_full,My_full,Mz_full])

zARM_oriented_directions=pmag.cart2dir(zARM_oriented)
zARMxARM_oriented_directions=pmag.cart2dir(zARMxARM_oriented)
zARMxARM_rotated_directions=pmag.cart2dir(zARMxARM_rotated)
```

```
#rotate the rotated directions about the z-axis to correspond to the oriented measurement
angle =  zARMxARM_oriented_directions.item(0) - zARMxARM_rotated_directions.item(0)

x_prime = PW15_data['Mx[Am2]'][378]*np.cos(np.radians(angle)) - PW15_data['My[Am2]'][378]*np.si
y_prime = PW15_data['Mx[Am2]'][378]*np.sin(np.radians(angle)) + PW15_data['My[Am2]'][378]*np.co
z_prime = PW15_data['Mz[Am2]'][378]

zARMxARM_rotated_prime = [[x_prime,y_prime,z_prime]]
zARMxARM_rotated_directions_prime=pmag.cart2dir(zARMxARM_rotated_prime)

#plot the oriented measurements and the rotated measurement
fignum = 1
plt.figure(num=fignum,figsize=(12,4),dpi=160)
ax1 = plt.subplot(121)
pmagplotlib.plotNET(fignum)
IPmag.iplotDI(zARM_oriented_directions,'r')
IPmag.iplotDI(zARMxARM_oriented_directions,'k')
IPmag.iplotDI(zARMxARM_rotated_directions,'b')
plt.title('zARM oriented (red) z&xARM oriented (black) and rotated (blue)');
plt.savefig('code_output/PW15-4d_eqarea_ARMex.svg')

#plot the oriented measurement and the corrected rotated measurement
ax1 = plt.subplot(122)
pmagplotlib.plotNET(fignum)
IPmag.iplotDI(zARMxARM_oriented_directions,'k')
IPmag.iplotDI(zARMxARM_rotated_directions_prime,'b')
plt.title('z&xARM  oriented (black) and rotated (corrected; blue)');
```




```
In [78]: #these values were needed to plot with the low-temp cycling data
         #on the vector component and equal area plot
         print zARM_oriented_directions
         print zARMxARM_rotated_directions_prime
```

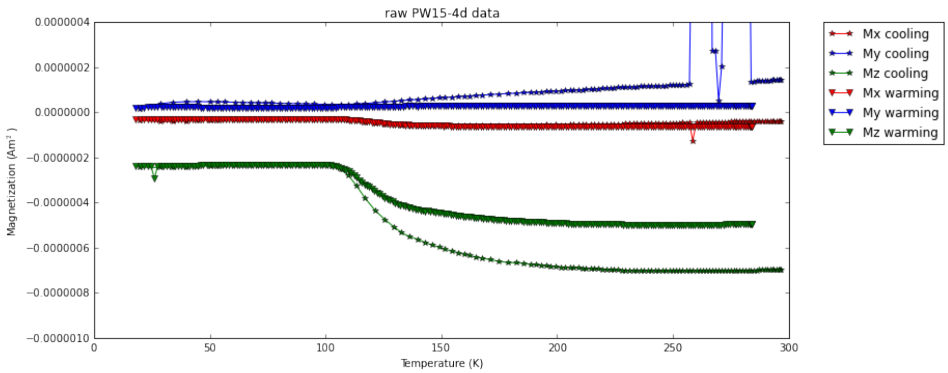
```
[[  2.74201770e+02  -8.45885759e+01   7.45321764e-07]]
[[  2.15129124e+02  -7.80651803e+01   7.16487969e-07]]
```

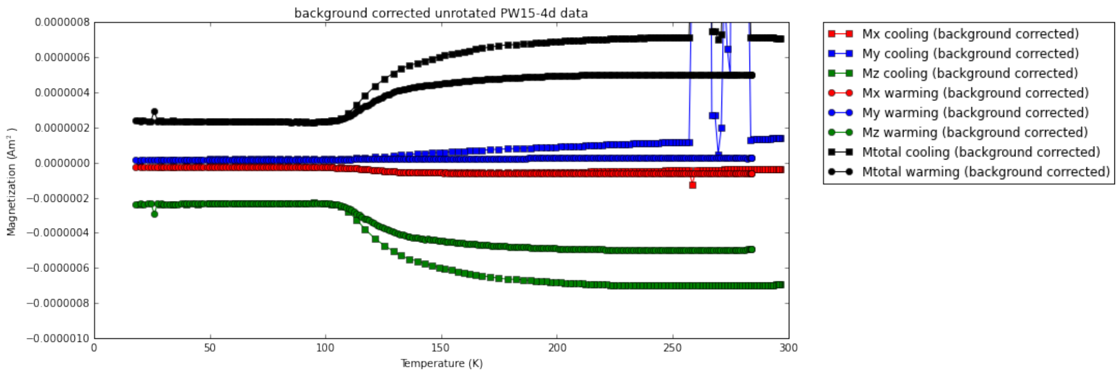
7.4.5 PW15-4d: Measurement series #4

```
In [79]: data_file_cooling='../Data/Umkondo/PW15/Pw15-4d_ARMex_cooling.txt'
         data_cooling = np.genfromtxt(data_file_cooling, skip_header=1)
```

```
temp_cooling=data_cooling[:,0]
Mx_cooling=data_cooling[:,1]
My_cooling=data_cooling[:,2]
Mz_cooling=data_cooling[:,3]
Mtotal_cooling=data_cooling[:,4]

data_file_warming='../Data/Umkondo/PW15/Pw15-4d_ARMex_warming.txt'
data_warming = np.genfromtxt(data_file_warming, skip_header=1)

temp_warming=data_warming[:,0]
Mx_warming=data_warming[:,1]
My_warming=data_warming[:,2]
Mz_warming=data_warming[:,3]
Mtotal_warming=data_warming[:,4]

#For the interpolate function to work the x values (temperature) need to be ascending.
#The blank_hem_data_cooling can be sorted so that temperatures are ascending
blank2_data_cooling = blank2_data_cooling.sort(['measurement_T[K]'])

Mx_cooling_bsub = background_sub(blank2_data_cooling['Mx[Am2]'],blank2_data_cooling['measuremer
                                 Mx_cooling,temp_cooling)

My_cooling_bsub = background_sub(blank2_data_cooling['My[Am2]'],blank2_data_cooling['measuremer
                                 My_cooling,temp_cooling)

Mz_cooling_bsub = background_sub(blank2_data_cooling['Mz[Am2]'],blank2_data_cooling['measuremer
                                 Mz_cooling,temp_cooling)

Mx_warming_bsub = background_sub(blank2_data_warming['Mx[Am2]'],blank2_data_warming['measuremer
                                 Mx_warming,temp_warming)

My_warming_bsub = background_sub(blank2_data_warming['My[Am2]'],blank2_data_warming['measuremer
                                 My_warming,temp_warming)

Mz_warming_bsub = background_sub(blank2_data_warming['Mz[Am2]'],blank2_data_warming['measuremer
                                 Mz_warming,temp_warming)

Mtotal_cooling_bsub=[]
Mtotal_warming_bsub=[]

for n in range(0,len(temp_cooling)):
    Mtotal_cooling_bsub.append(np.sqrt(Mx_cooling_bsub[n]**2+My_cooling_bsub[n]**2+Mz_cooling_

for n in range(0,len(temp_warming)):
    Mtotal_warming_bsub.append(np.sqrt(Mx_warming_bsub[n]**2+My_warming_bsub[n]**2+Mz_warming_

fignum=1
plt.figure(num=fignum,figsize=(12,12),dpi=160)

ax=plt.subplot(211)
plt.plot(temp_cooling, Mx_cooling, 'r*-',label="Mx cooling")
plt.plot(temp_cooling, My_cooling, 'b*-',label="My cooling")
plt.plot(temp_cooling, Mz_cooling, 'g*-',label="Mz cooling")
```

```
plt.plot(temp_warming, Mx_warming, 'rv-',label="Mx warming")
plt.plot(temp_warming, My_warming, 'bv-',label="My warming")
plt.plot(temp_warming, Mz_warming, 'gv-',label="Mz warming")
plt.xlabel('Temperature (K)')
plt.ylabel('Magnetization (Am$^2$)')
plt.axis([0, 300, -0.000001, 0.0000004])
plt.title('raw PW15-4d data')
plt.legend(bbox_to_anchor=(1.05, 1), loc=2, borderaxespad=0.)

ax=plt.subplot(212)
plt.plot(temp_cooling, Mx_cooling_bsub, 'rs-',
         label="Mx cooling (background corrected)")
plt.plot(temp_cooling, My_cooling_bsub, 'bs-',
         label="My cooling (background corrected)")
plt.plot(temp_cooling, Mz_cooling_bsub, 'gs-',
         label="Mz cooling (background corrected)")
plt.plot(temp_warming, Mx_warming_bsub, 'ro-',
         label="Mx warming (background corrected)")
plt.plot(temp_warming, My_warming_bsub, 'bo-',
         label="My warming (background corrected)")
plt.plot(temp_warming, Mz_warming_bsub, 'go-',
         label="Mz warming (background corrected)")
plt.plot(temp_cooling, Mtotal_cooling_bsub, 'ks-',
         label="Mtotal cooling (background corrected)")
plt.plot(temp_warming, Mtotal_warming_bsub, 'ko-',
         label="Mtotal warming (background corrected)")
plt.xlabel('Temperature (K)')
plt.ylabel('Magnetization (Am$^2$)')
plt.legend(bbox_to_anchor=(1.05, 1), loc=2, borderaxespad=0.)
plt.title('background corrected unrotated PW15-4d data')
plt.axis([0, 300, -0.000001, 0.0000008])
plt.show()
```





The fan turning on and off on another instrument in the lab resulted in flux jumps during a portion of time during initial cooling. These data need to be filtered out of the data set which is done below. The data also need to be rotated into the specimen's core coordinates.

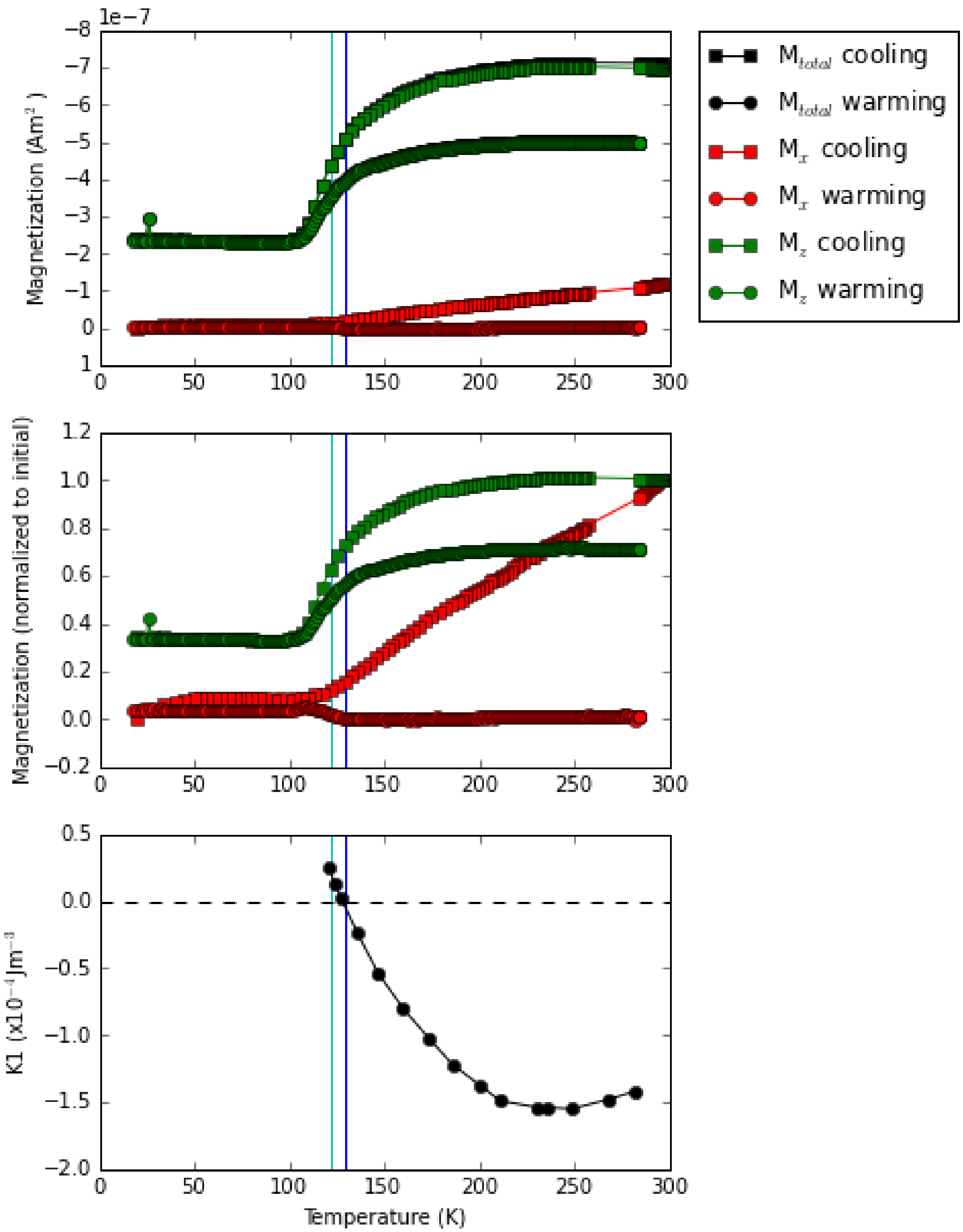
```
In [80]: Mx_cooling_prime = Mx_cooling_bsub*np.cos(np.radians(angle)) - My_cooling_bsub*np.sin(np.radia
         My_cooling_prime = Mx_cooling_bsub*np.sin(np.radians(angle)) + My_cooling_bsub*np.cos(np.radia
         Mz_cooling_prime = Mz_cooling_bsub
         Mx_cooling_prime_nf = []
         My_cooling_prime_nf = []
         Mz_cooling_prime_nf = []
         Mtotal_cooling_prime_nf = []
         full_vector_cooling=[]
         temp_cooling_prime = []
         temp_cooling_prime_nf = []

         for n in range(0,len(temp_cooling)):
             if My_cooling[n] < 1.45000000e-07 and temp_cooling[n] != 269.77999999999997: #this filter
                 Mx_cooling_prime_nf.append(Mx_cooling_prime[n])
                 My_cooling_prime_nf.append(My_cooling_prime[n])
                 Mz_cooling_prime_nf.append(Mz_cooling_prime[n])
                 temp_cooling_prime_nf.append(temp_cooling[n])
                 Mtotal_cooling_prime_nf.append(np.sqrt(Mx_cooling_prime[n]**2+My_cooling_prime[n]**2+M
                 full_vector_cooling.append([Mx_cooling_prime[n],My_cooling_prime[n],Mz_cooling_prime[n

         Mx_warming_prime = Mx_warming_bsub*np.cos(np.radians(angle)) - My_warming_bsub*np.sin(np.radia
         My_warming_prime = Mx_warming_bsub*np.sin(np.radians(angle)) + My_warming_bsub*np.cos(np.radia
         Mz_warming_prime = Mz_warming_bsub
```

```
Mtotal_warming_prime= []
full_vector_warming=[]

for n in range(0,len(temp_warming)):
    full_vector_warming.append([Mx_warming_prime[n],My_warming_prime[n],Mz_warming_prime[n]])
    Mtotal_warming_prime.append(np.sqrt(Mx_warming_prime[n]**2+My_warming_prime[n]**2+Mz_warmi
```

These rotated, background corrected data are plotted below along with data that shows the change in magnetocrystalline anisotropy as a function of temperature for the sake of comparision with the patterns of demagnetization observed for the z-axis component (full ARM up to 200 mT except 0 to 5 mT) and the x-axis pARM (applied to low coercivity grains with a 0 to 5 mT AF field).

```
In [81]: fignum=2
         plt.figure(num=fignum,figsize=(5,10),dpi=160)
         ax=plt.subplot(311)
         plt.plot(temp_cooling_prime_nf, np.negative(Mtotal_cooling_prime_nf), 'ks-',label="M$_{total}$
         plt.plot(temp_warming, np.negative(Mtotal_warming_prime), 'ko-',label="M$_{total}$ warming")
         plt.plot(temp_cooling_prime_nf, Mx_cooling_prime_nf, 'rs-',label="M$_x$ cooling")
         plt.plot(temp_warming, Mx_warming_prime, 'ro-',label="M$_x$ warming")
         #plt.plot(temp_cooling_prime_nf, My_cooling_prime_nf, 'bs-',label="M£_y£ cooling")
         #plt.plot(temp_warming, My_warming_prime, 'bo-',label="M£_y£ warming")
         plt.plot(temp_cooling_prime_nf, Mz_cooling_prime_nf, 'gs-',label="M$_z$ cooling")
         plt.plot(temp_warming, Mz_warming_prime, 'go-',label="M$_z$ warming")
         plt.vlines(130, 1e-7,-8e-7, colors='b')
         plt.vlines(122, 1e-7,-8e-7, colors='c')
         plt.legend(bbox_to_anchor=(1.05, 1), loc=2, borderaxespad=0.)
         plt.ylabel('Magnetization (Am$^2$)')
         #plt.title('background corrected and rotated PW6-5f data')
         plt.ylim(1e-7,-8e-7)
         plt.savefig('PW15-4d_3axisLTD_ARMex.svg')

         ax=plt.subplot(312)
         plt.plot(temp_cooling_prime_nf, Mx_cooling_prime_nf/Mx_cooling_prime_nf[0], 'rs-',label="Mx co
         plt.plot(temp_warming, Mx_warming_prime/Mx_cooling_prime_nf[0], 'ro-',label="Mx warming")
         plt.plot(temp_cooling_prime_nf, Mz_cooling_prime_nf/Mz_cooling_prime_nf[0], 'gs-',label="Mx co
         plt.plot(temp_warming, Mz_warming_prime/Mz_cooling_prime_nf[0], 'go-',label="Mx warming")
         plt.vlines(130, -.2, 1.2, colors='b')
         plt.vlines(122, -.2, 1.2, colors='c')
         #plt.legend(bbox_to_anchor=(1.05, 1), loc=2, borderaxespad=0.)
         plt.ylabel('Magnetization (normalized to initial)')
         #plt.title('background corrected and rotated PW6-5f data')
         plt.ylim(-.2, 1.2)
         plt.savefig('PW15-4d_3axisLTD_ARMex.svg')

         Bickford_data = pd.read_csv('../Data/Umkondo/Bickford1957a_data.csv')

         ax=plt.subplot(313)
         plt.plot(Bickford_data['temp'],Bickford_data['Kone'],'ko-')
         plt.vlines(130, -2, 0.5, colors='b')
         plt.vlines(122, -2, 0.5, colors='c')
         plt.hlines(0, 0, 300, colors='k',linestyles='--')
         plt.xlim(0,300)
         plt.ylim(-2,0.5)
         plt.xlabel('Temperature (K)')
         plt.ylabel('K1 (x10$^{-4}$Jm$^{-3}$')
```

```
cooling_directions=pmag.cart2dir(full_vector_cooling)
warming_directions=pmag.cart2dir(full_vector_warming)

plt.savefig('code_output/PW15-4d_3axisLTD_ARMex.pdf')
```



Let's export the data in order to make a space-delimited file to be plotted using the PmagPy program zeq.py outside of this IPython notebook.

```
In [82]: np.savetxt("code_output/PW15-4d_cooling.txt", cooling_directions, delimiter=" ")
         np.savetxt("code_output/PW15-4d_coolingtemp.txt", temp_cooling_prime_nf, delimiter=" ")
         np.savetxt("code_output/PW15-4d_warming.txt", warming_directions, delimiter=" ")
         np.savetxt("code_output/PW15-4d_warmingtemp.txt", temp_warming, delimiter=" ")
         lowT_endpoint = warming_directions[len(warming_directions)-1]
         print lowT_endpoint
```

```
[  2.68489944e+02  -8.23278382e+01   4.99277242e-07]
```

Another figure to make is to compare the direction of the z-axis ARM with the z-axis ARM + x-axis pARM with the end point following low-temperature cycling.

```
In [83]: fignum = 1
         plt.figure(num=fignum,figsize=(6,6),dpi=160)
         pmagplotlib.plotNET(fignum)
         IPmag.iplotDI(zARM_oriented_directions,'r')
         IPmag.iplotDI(zARMxARM_rotated_directions_prime,'k')
         IPmag.iplotDI([[268.4,-82.3]],'b')
         plt.title('PW15-4d zARM oriented (red) z&xARM oriented (black) and following lowT-demag (blue)
         plt.savefig('code_output/PW15-4d_eqarea_ARMex.svg')
```