ART Applied Robotics Technologies
A spinoff company for the commercialization of robotics research at the University of Michigan
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Re: Results of calibration of five KVH E-Core fiber optic gyroscopes

ART has completed the calibration of five KVH E-Core RD2100 fiber optic gyroscopes:

ART #	Gyro #1	Gyro #2	Gyro #3	Gyro #4	Gyro #5
KVH S/N	NAVC3545	NAVC4361	NAVC4058	NAVC4377	NAVC4253

Section 1 of this report includes the instructions for implementing the calibration parameters in the user's robot navigation program.

Section 2 of this report includes the individual pre- and post calibration results, along with the calibration parameters as determined by the ***ART*** calibration procedure.

We recommend that personell involved in the implementation of gyro calibration parameters familiarize themselves with our paper that describes the theory and implementation of our gyro calibration procedure. The paper is available for downloading at
ftp://ftp.eecs.umich.edu/people/johannb/paper82.pdf
(Simply copy this this line into the address field of your browser.)

However, should you have any further questions please don't hesitate to contact me.

Sincerely,

Johann Borenstein
Founder, Applied Robotics Technologies

1. PROGRAMMING INSTRUCTIONS

```
/*
   THE FOLLOWING PROGRAM EXCERPTS DEMONSTRATE THE IMPLEMENTATION OF THE ART GYRO CALIBRATION.
   THE USER MUST PROVIDE THE SERIAL INTERFACE FUNCTION THAT READS THE GYROSCOPE DATA
   FOR THE EXAMPLE HERE WE ASSUME THAT THE USER'S FUNCTION FOLLOWS THIS PROTOTYPE:

      void GetDataGyro(float &RawGyroRate,float &RawGyroTemp);

   ------------------------------------------------------------------------------------------------
   FOR EVERY CALIBRATED GYROSCOPE ART PROVIDES PARAMETERS SIMILAR TO THE ONES IN THIS EXAMPLE:

   SCALE FACTOR
   0.00305
   ------------ POLYNOMIAL FUNCTION
   ROWS 3
   COLUMNS 4
   coef:
       0.00000000012313   0.00000000143238  -0.00000534016111   0.00002859513716
      -0.00000000943186  -0.00000013827389   0.00040498854550  -0.00273529496803
       0.00000146111920   0.00000036044534  -0.00858852574742   0.04876704353858

   THESES PARAMETERS HAVE TO BE INTEGRATED IN THE CODE AS FOLLOWS:
*/

#define BIAS_SAMPLES 100           //10 SECONDS OF STATIC BIAS DRIFT CALCULATION
#define TEMP_SCALE_FACTOR 0.05     //THIS PARAMETER IS CONSTANT FOR ALL THE GYROSCOPES 0.05
#define RATE_SCALE_FACTOR 0.00305  //THIS PARAMETER RARELY CHANGES FOR MOST OF THE GYROSCOPES IT IS 0.00305
#define ROWS 3                     //COEFICIENT MATRIX ROWS
#define COLUMNS 4                  //COEFICIENT MATRIX COLUMNS

//THIS MATRIX IS COMPOSED OF THE PARAMETERS OBTAINED DURING THE CALIBRATION PROCESS
coef[ROWS][COLUMNS]={{ 0.00000000012313,   0.00000000143238,  -0.00000534016111,   0.00002859513716}
                     {-0.00000000943186,  -0.00000013827389,   0.00040498854550,  -0.00273529496803},
                     { 0.00000146111920,   0.00000036044534,  -0.00858852574742,   0.04876704353858}};

//GLOBAL VARIABLES
float StaticBiasDrift;
float CalcStaticBiasDrift;

//THIS FUNCTION COMPUTES THE ERROR CORRECTION BASED ON THE COMPENSATION FUNTION DEFINED BY THE MATRIX 'coef'
//    GyroRate = GYRO RATE OF TURN
//    GyroTemp = GYRO TEMPERATURE
float CompFunction(float GyroRate,float GyroTemp)
{
   float sumT[10];
   float Aux;
   int i,j;
   float comp=0;
   for(i=0;i<COLUMNS;i++)
   {
      sumT[i]=0;
      for(j=0;j<ROWS;j++)
      {
         Aux=(ROWS-j-1)?pow(GyroTemp,ROWS-j-1):1;
         sumT[i]+=Aux*coef[j][i];
      }
   }
   for(i=0;i<COLUMNS;i++)
   {
      Aux=(COLUMNS-i-1)?pow(GyroRate,COLUMNS-i-1):1;
      comp+=Aux*sumT[i];
   }
   return comp;
}
```

//CALCULATING THE STATIC BIAS DRIFT:

```
// THIS FUNCTION CALCULATES THE FOLLOWING TWO PARAMETERS:
// StaticBiasDrift
// CalcStaticBiasDrift

void StaticBias()
{
   float RawGyroRate;
   float RawGyroRate;
   float GyroTemp;
   float RawGyroTemp;

   float SumB=0;
   float SumC=0;
   for(int i=0;i<BIAS_SAMPLES;i++)
   {
      GetDataGyro(RawGyroRate,RawGyroTemp);
      SumB+=RawGyroRate;
      GyroRate=RateConvFactor*RawGyroRate;
      GyroTemp=TEMP_SCALE_FACTOR*RawGyroTemp;
      SumC+=CompFunction(GyroRate,GyroTemp);
   }
   StaticBiasDrift=SumB*RateConvFactor/BIAS_SAMPLES;
   CalcStaticBiasDrift=SumC/BIAS_SAMPLES;
}
```

//SAMPLE PROGRAM

```
void main()
{
   float RawGyroRate;
   float RawGyroRate;
   float GyroTemp;
   float RawGyroTemp;
   float CompRate;
   //COMPUTE THE STATIC BIAS DRIFT WHILE THE ROBOT IS STATIONARY
   StaticBias()

   while(!kbhit())
   {
      GetDataGyro(RawGyroRate,RawGyroTemp);
      GyroRate=RateConvFactor*RawGyroRate;
      GyroTemp=TEMP_SCALE_FACTOR*RawGyroTemp;
      //Compensate gyro readings
      comp=CompFunction(GyroRate,GyroTemp);
      //Correction using the actual bias
      CompRate=GyroRate-StaticBiasDrift-comp+CalcStaticBiasDrift;
      printf("Rate=%f CompRate%f",GyroRate,CompRate)
   }
}
```

2. INDIVIDUAL CALIBRATION RESULTS

The ***ART*** calibration process was successfully applied to all five gyros. The results are shown in the following pages.

Notes:

1. We found that the behaviour of gyro #3 differed significantly from that of the other four gyros in this batch (and, in fact, from all of the gyros we calibrated to date). While the results after calibration appear to be acceptable and comparable to those of the other gyros, we recommend that caution be exercised in using this gyro.

2. Please be sure you understand the need for what we call the "Static Bias Drift Calibration" prior to every robot run. This procedure is explained in Section 2 of our paper, and this section is repeated here for your convenience.

STATIC BIAS DRIFT CALIBRATION

A common compensation procedure for static bias drift (see Figure 1) is to collect several samples (for, say, 10-20 seconds) with the gyro stationary and *immediately prior to every mission*.

Specifically, this is done by computing

$$\omega_s = \frac{1}{n}\sum_{i=1}^{n}\omega_{g,i} \qquad (1)$$

where

ω_s - static bias drift

n - total number of samples (n = 100 for a 10-second sample with the RD2100)

During the immediately following mission, ω_s is subtracted from subsequent measurements ω_g. Since the static bias drift is small for the RD2100, this technique will assure that errors due to static bias drift will be less than about one degree for subsequent missions of fewer than 10 minutes of duration. Note that ω_s also includes the rate-of-rotation component introduced by the earth's rotation.

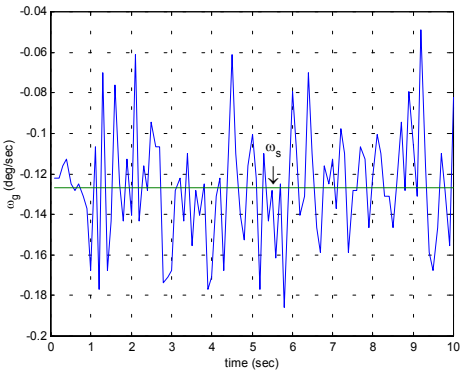


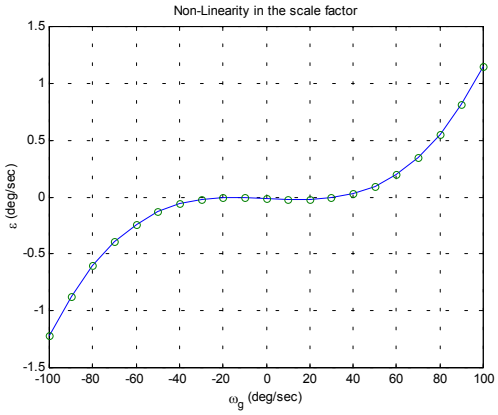
Figure 1: Example of Static Bias Drift. Output readings of the stationary gyro over a 10- seconds period. The average of these readings is the *momentary static bias drift*.

It is important that the static bias drift calibration be performed as described prior to every mission because the thus determined ω_s (=`CalcStaticBiasDrift` in the program above) is used every time the calibration function is applied to the raw gyro readings.

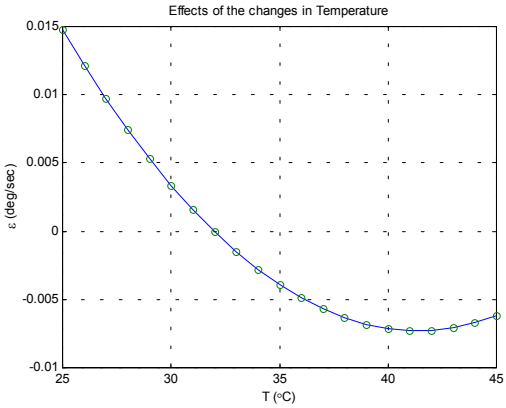
Gyro #1, S/N: NAVC3545

Polynomial function with ROWS = 3, COLUMNS = 4, Scale Factor = 0.00305:

```
 0.00000000012313   0.00000000143238  -0.00000534016111   0.00002859513716
-0.00000000943186  -0.00000013827389   0.00040498854550  -0.00273529496803
 0.00000146111920   0.00000036044534  -0.00858852574742   0.04876704353858
```

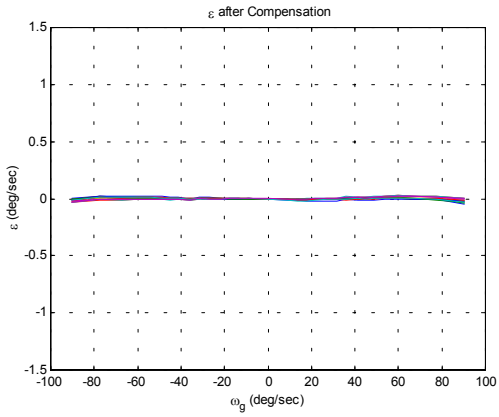


Non-linearity of the scale factor, shown for different rates of rotation, at a constant temperature, for the uncalibrated gyro.

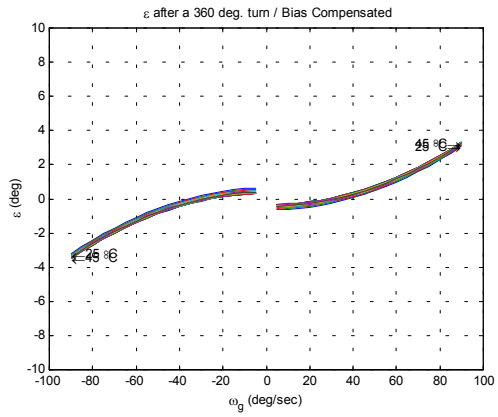


Temperature dependency, shown for different temperatures at a constant rate of rotation, for the uncalibrated gyro.

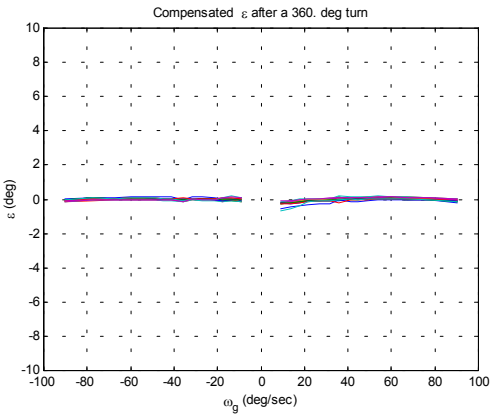
Errors of the uncalibrated gyro over the whole range of rates of rotation and temperatures.



Errors of the ***ART***-calibrated gyro over the whole range of rates of rotation and temperatures[1].



Errors after a full 360° turn, for the uncalibrated gyro[1].



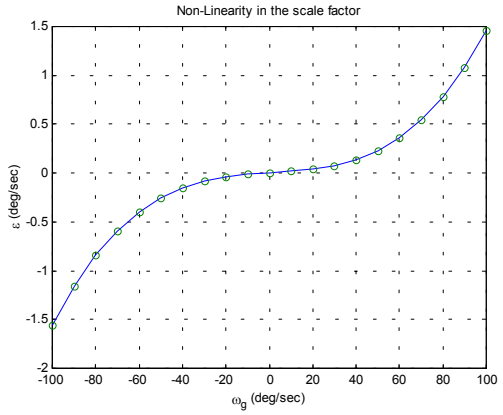
Errors after a full 360° turn, for the ***ART*** calibrated gyro[1].

1) Different temperatures are shown as lines of different colors. In the graphs of errors *after* ***ART*** calibration the temperature-based variations are so small that they are barely distinguishable.

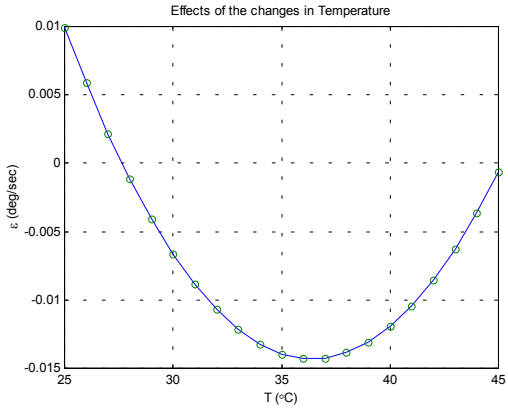
Gyro #2, S/N: NAVC4361

Polynomial function with ROWS = 3, COLUMNS = 4, Scale Factor = 0.00305:

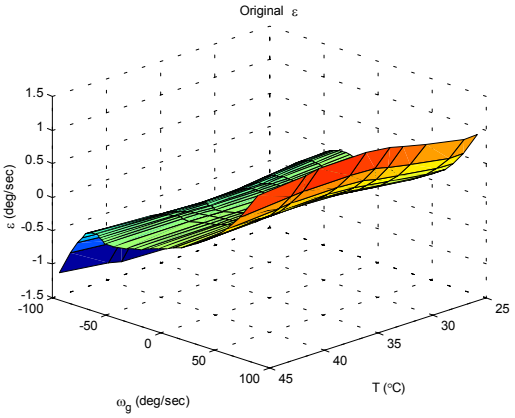
```
-0.00000000020358   0.00000000945730  -0.00001839079370   0.00000067971730
 0.00000000966230  -0.00000070089413   0.00141489985827   0.00069842373067
 0.00000127306191   0.00000763722563  -0.02543628133507  -0.02175919188879
```



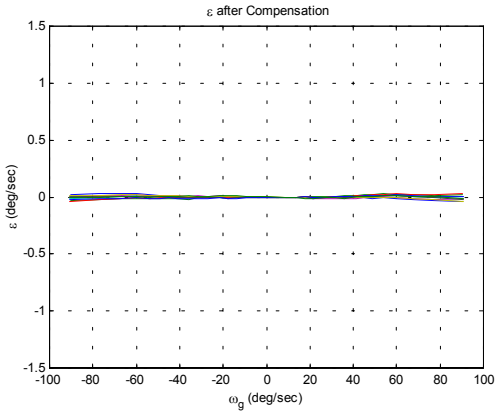
Non-linearity of the scale factor, shown for different rates of rotation, at a constant temperature, for the uncalibrated gyro.



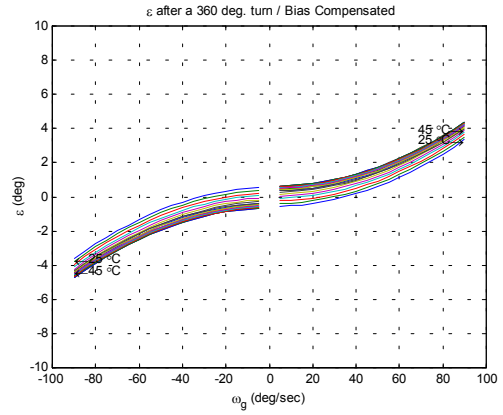
Temperature dependency, shown for different temperatures at a constant rate of rotation, for the uncalibrated gyro.



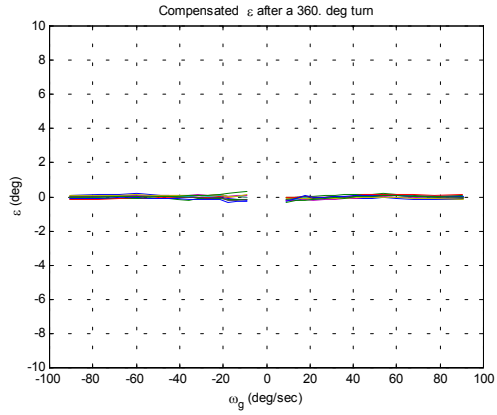
Errors of the uncalibrated gyro over the whole range of rates of rotation and temperatures.



Errors of the ***ART***-calibrated gyro over the whole range of rates of rotation and temperatures[1].



Errors after a full 360° turn, for the uncalibrated gyro[1].



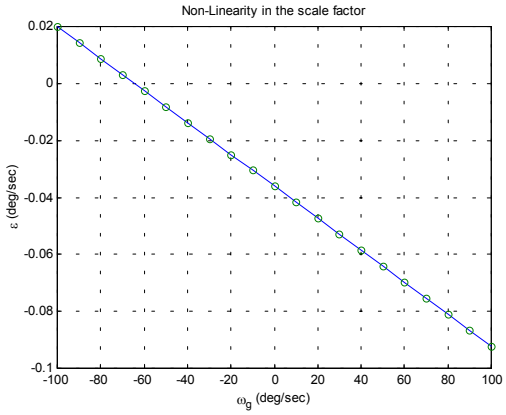
Errors after a full 360° turn, for the ***ART*** calibrated gyro[1].

1) Different temperatures are shown as lines of different colors. In the graphs of errors *after* ***ART*** calibration the temperature-based variations are so small that they are barely distinguishable.

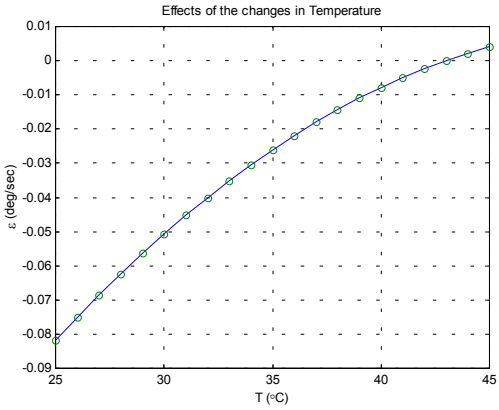
Gyro #3, S/N: NAVC4058

Polynomial function with ROWS = 3, COLUMNS = 2, Scale Factor = 0.00283:

```
  0.00002393343232   0.00011192340532
 -0.00179428584902  -0.00473657773294
  0.03277807530338  -0.00443055269265
```

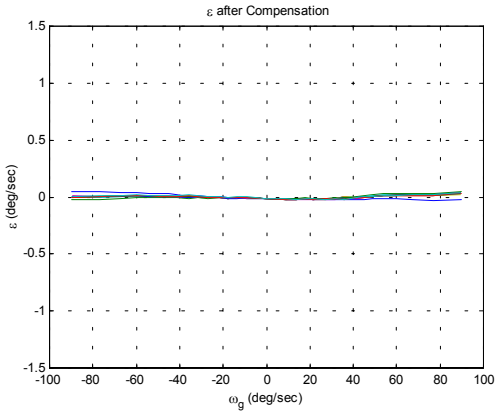


Non-linearity of the scale factor, shown for different rates of rotation, at a constant temperature, for the uncalibrated gyro.

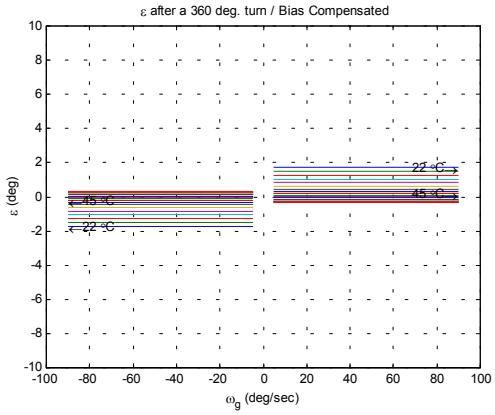


Temperature dependency, shown for different temperatures at a constant rate of rotation, for the uncalibrated gyro.

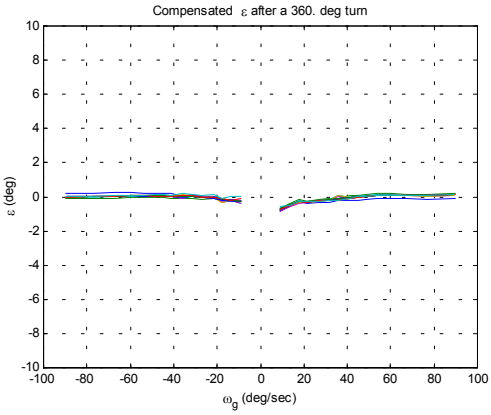
Errors of the uncalibrated gyro over the whole range of rates of rotation and temperatures.



Errors of the ***ART***-calibrated gyro over the whole range of rates of rotation and temperatures[1].



Errors after a full 360° turn, for the uncalibrated gyro[1].



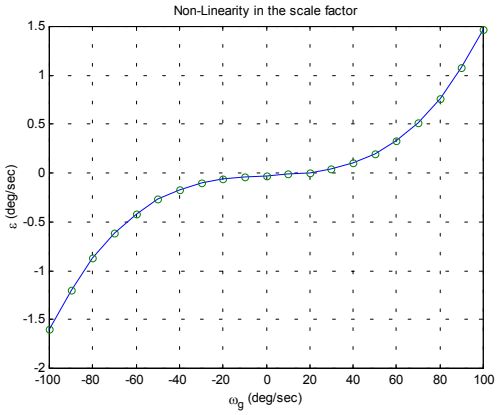
Errors after a full 360° turn, for the ***ART*** calibrated gyro[1].

1) Different temperatures are shown as lines of different colors. In the graphs of errors *after* ***ART*** calibration the temperature-based variations are so small that they are barely distinguishable.

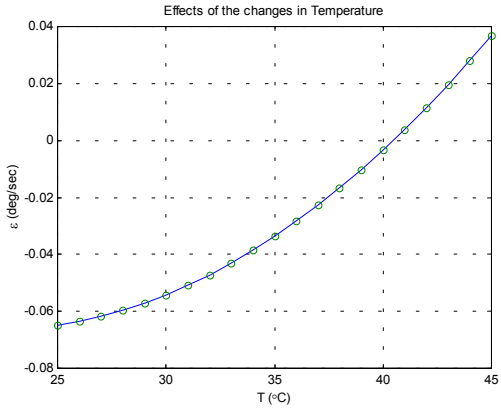
Gyro #4, S/N: NAVC4377

Polynomial function with ROWS = 3, COLUMNS = 4, Scale Factor = 0.00305:

```
 0.00000000012646  -0.00000000025438  -0.00001238671287   0.00007279729207
-0.00000000791885  -0.00000003080748   0.00043948634750  -0.00428204162041
 0.00000154521837  -0.00000297275241   0.00048725340306   0.03585268629915
```

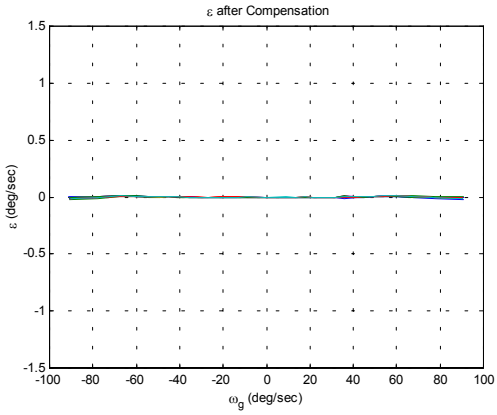


Non-linearity of the scale factor, shown for different rates of rotation, at a constant temperature, for the uncalibrated gyro.

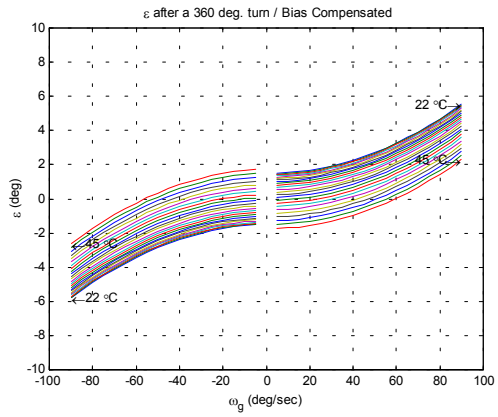


Temperature dependency, shown for different temperatures at a constant rate of rotation, for the uncalibrated gyro.

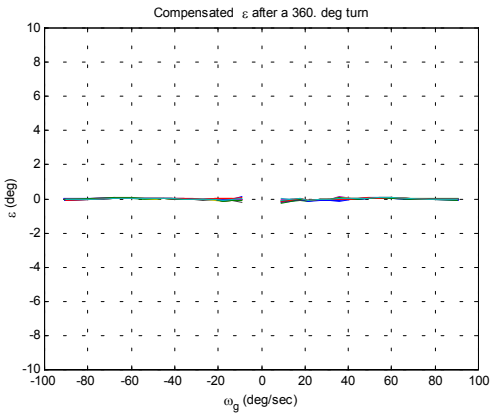
Errors of the uncalibrated gyro over the whole range of rates of rotation and temperatures.



Errors of the ***ART***-calibrated gyro over the whole range of rates of rotation and temperatures[1].



Errors after a full 360° turn, for the uncalibrated gyro[1].



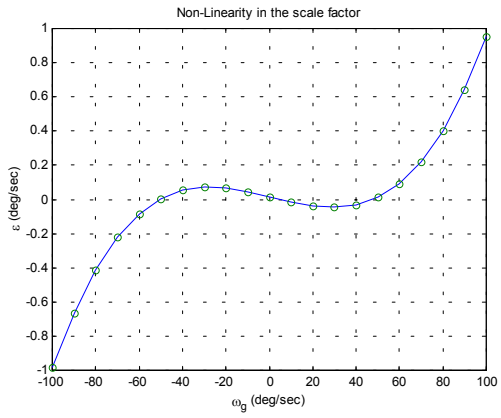
Errors after a full 360° turn, for the ***ART*** calibrated gyro[1].

1) Different temperatures are shown as lines of different colors. In the graphs of errors *after* ***ART*** calibration the temperature-based variations are so small that they are barely distinguishable.

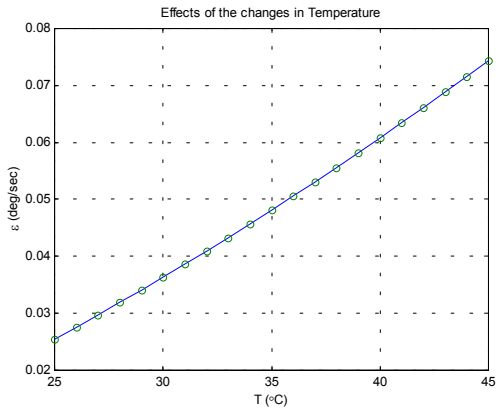
Gyro #5, S/N: NAVC4253

Polynomial function with ROWS = 3, COLUMNS = 4, Scale Factor = 0.00305:

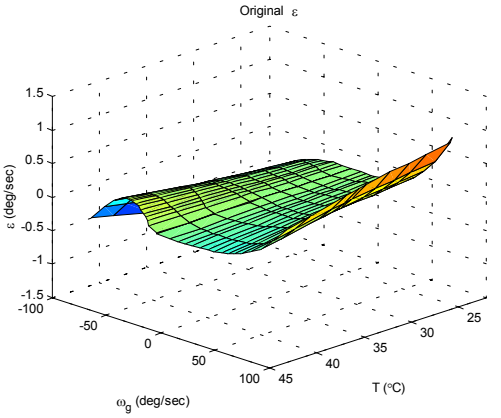
```
 0.00000000013463   0.00000000407842  -0.00000475160031  -0.00002877047062
-0.00000001147802  -0.00000033069787   0.00002127221377   0.00134898688138
 0.00000151459989   0.00000324190249   0.00165290643492   0.00348922163647
```



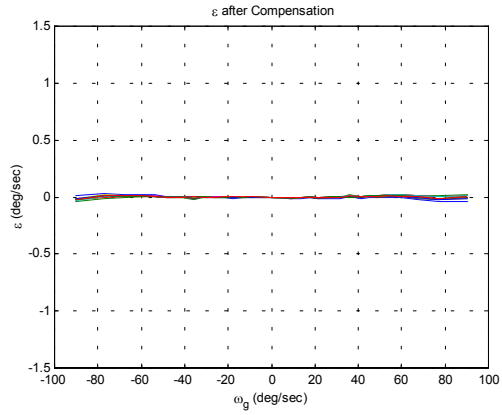
Non-linearity of the scale factor, shown for different rates of rotation, at a constant temperature, for the uncalibrated gyro.



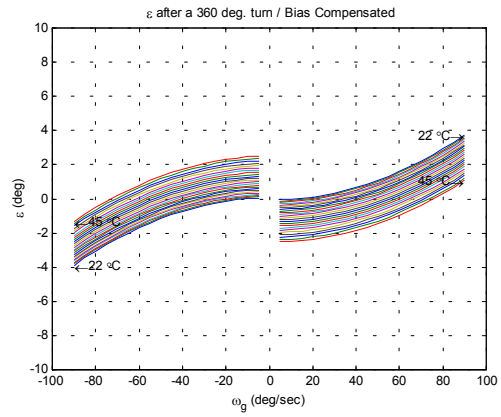
Temperature dependency, shown for different temperatures at a constant rate of rotation, for the uncalibrated gyro.



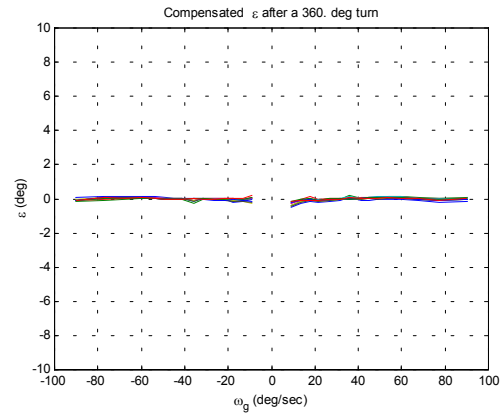
Errors of the uncalibrated gyro over the whole range of rates of rotation and temperatures.



Errors of the ***ART***-calibrated gyro over the whole range of rates of rotation and temperatures[1].



Errors after a full 360° turn, for the uncalibrated gyro[1].



Errors after a full 360° turn, for the ***ART*** calibrated gyro[1].

1) Different temperatures are shown as lines of different colors. In the graphs of errors *after* ***ART*** calibration the temperature-based variations are so small that they are barely distinguishable.