NuSim Manual

Written
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Abstract

Here go NuSim abstract.

Preface

Here be a preface.

Acknowledgement

Here go acknowledgements.

Contents

Chapter 1

Install

1.1 NuSIM quick installation instructions

1.1.1 Installation ROOT

The first prerequisite is ROOT. Here are some tips for the ROOT installation

- For the current version make sure you have installed at least version 5.22 higher is probably better, but do not install a version with an uneven minor version number, e.g. 5.25, 5.27 as those are development versions

- Make sure you dont mix 32 bit and 64 bit (i.e. if you compile NuSIM as 64 bit, you also need a 64 bit ROOT).

- Do not forget to set all ROOT variables, i.e. ROOTSYS (pointing to the directory where ROOT is installed), and add ROOT to the PATH and LD_LIBRARY_PATH (or DYLD_LIBRARY_PATH an Mac) variables if you install ROOT in a place not yet included in those paths.

1.1.2 HEAsoft

In order to read and write fits files, HEAsoft is required. A standard installation should do, but take into account the following things:

- NuSIMs configuration tool verifies that HEAsoft is installed only by checking of the HEADAS environment variable is set.

- It seems that on the latest HEADAS installations the required libcfitsio.[so/dylib] (so: Linux, dylib: Mac) does not exist but only a version one, e.g. libcfitsio_34.so. Since NuSIM should be able to run with any version of libcfitsio you might have to make a link, e.g. do: ln s libcfitsio_3.24.[so/dylib] libcfitsio.[so/dylib] in the heasoft/<system version>/lib directory.

1.1.3 NuSIM

Next, retrieve NuSIM from its repository by using subversion:

```
svn co https://www.srl.caltech.edu/svn/nusim/trunk nusim
```

Old versions before 0.9.0 can be found in:

```
svn co https://www.srl.caltech.edu/svn/nustar/trunk/nusim nusim
```

Please ask Andrew Davis (ad@srl.caltech.edu) for a svn login and password.

The above command should have generated the directory nusim with all the source code.

Then set all your paths correctly (the paths are set in a similar way to your ROOT paths this example is using bash on Linux):

```
export NUSIM=${some directory}/nusim
export PATH=${NUSIM}/bin:$PATH
```

For Linux (attention: in some system this variable might not yet have been defined!)

```
export LD_LIBRARY_PATH=${NUSIM}/lib:${LD_LIBRARY_PATH}
```

For Mac OS X (attention: in some system this variable might not yet have been defined!):

```
export DYLD_LIBRARY_PATH=${NUSIM}/lib:${DYLD_LIBRARY_PATH}
```

The configure NuSIM cd $NUSIM For Linux: sh configure -linux -debug For Mac OS X: sh configure -macosx debug This is followed by a simple: make (No make install for the time being!)

If you launch NuSIM the first time, or if you expect that the configuration file format has been changed, launch NuSIM with the default configuration:

```
cd \$NUSIM
nusim -c resources/configurations/Ideal.cfg
```

Several more NuSIM configuration files can be found in the resources/configurations directory. Now you should be able to play around with NuSIM.

Some more tips:

- Calling make man creates doxygen documentation. Make sure you have doxygen & graphviz installed.
- If you update NuSIM make sure to completely recompile NuSIM: make clean followed by make. Otherwise you might experience unexpected crashes or weird behaviour.

1.1.4 Frequently asked questions

Example configuration

For Linux with bash the configuration files should look similar to this. Do NOT simply copy and paste this to your .bashrc-file! You have to adapt it to your own system! This is just an example, to check if you forgot something! Attention: The sequence does matter, since e.g. HEAsoft and ROOT have libraries which are named the same way. In addition, HEAsoft provides its own version of libreadline.so, which might interfere with system maintenance as super-user root.

```
PRG=/prg

# HEASOFT
if [ "$USER" != "root" ]; then
  export HEADAS=${PRG}/headas/i686-pc-linux-gnu-libc2.5
  alias heainit=". $HEADAS/headas-init.sh"
  source $HEADAS/headas-init.sh
fi

# ROOT
export ROOTSYS=${PRG}/root
export PATH=$PATH:$ROOTSYS/bin
export LD_LIBRARY_PATH=$ROOTSYS/lib:$LD_LIBRARY_PATH

# NUSIM
export NUSIM=${SOFTWARE}/Nusim
export PATH=${NUSIM}/bin:$PATH
export LD_LIBRARY_PATH=${NUSIM}/lib:${LD_LIBRARY_PATH}
```

ROOT compilation problems

Error message similar to:

```
Compiling XrdNetDNS.cc
g++ -c -D_LARGEFILE_SOURCE -D_LARGEFILE64_SOURCE -D_FILE_OFFSET_BITS=64
-D_REENTRANT -D_GNU_SOURCE -Wall -D__macos__
-Wno-deprecated -undefined dynamic_lookup -multiply_defined suppress  -O2 -DXrdDEBUG=0
     -I. -I.. XrdNetDNS.cc -o ../../obj/XrdNetDNS.o
XrdNetDNS.cc: In static member function 'static int XrdNetDNS::getHostAddr(const char*, sockaddr*, int, char**)':
XrdNetDNS.cc:73: error: 'gethostbyname_r' was not declared in this scope
XrdNetDNS.cc:82: error: 'gethostbyaddr_r' was not declared in this scope
XrdNetDNS.cc: In static member function 'static int XrdNetDNS::getPort(const char*, const char*, char**)':
XrdNetDNS.cc:393: error: 'getservbyname_r' was not declared in this scope
make[5]: *** [../../obj/XrdNetDNS.o] Error 1
make[4]: *** [Darwinall] Error 2
make[3]: *** [all] Error 2
make[2]: *** [XrdNet] Error 2
make[1]: *** [all] Error 2
make: *** [net/xrootd/src/xrootd/lib/libXrdSec.so] Error 2
```

The Xrd component of ROOT has sophisticated dependencies, but it is not required for NuSIM. Thus simply disable it during ROOT configuration with:

```
./configure -disable-xrootd
```

NuSIM configuration/compilation problems

Error message similar to:

```
(2) ROOT

Found ROOT: /home/andreas/prg/root/bin/root
Found ROOT version: 5.26/00 (minimum: 5.22, maximum: 5.28)
[: 108: ==: unexpected operator
```

You didnt use bash to run configure or you didnt start configure with: ./configure

Error message: Generating dictionary... This may take a while... rootcint: error while loading shared libraries: libCint.so: cannot open shared object file: No such file or directory

Something is wrong with your ROOT installation:

- Did you install ROOT correctly?
- Does your LD_LIBRARY path contain the correct settings for ROOT?

Error message: Library not found for -lcfitsio

Something is wrong with your HEAsoft installation:

- Your system has only a versioned version of libcfitsio, e.g. libcfitsio_34.so but no libcfitsio.so. Since the version ID changes from HEAsoft version to HEAsoft version, HEAsoft should contain a link from the versioned to the unversioned library. but it doesnt. Therefore you have to make it yourself: ln s libcfitsio_3.24.[so/dylib] libcfitsio.[so/dylib] in the heasoft/¡system version¿/lib directory.
- If the above is not the problem, most likely HEAsoft is not or not correctly installed.

NuSIM execution problems

The NuSIM GUI program crashes with an error message like (or you see no GUI at all or have funny fonts):

```
Attaching to program: /proc/29042/exe, process 29042 done.
[Thread debugging using libthread\_db enabled]
[New Thread 0x7f9e513606f0 (LWP 29042)]
0x00007f9e49a1ffd5 in waitpid () from /lib/libc.so.6 error detected on stdin
The program is running.  Quit anyway (and detach it)? (y or n) [answered Y; input not from terminal]
Detaching from program: /proc/29042/exe, process 29042
```

Some Xft implementations (Xft is used for font smoothing) seem to have problems how ROOT is using them. You have to reconfigure ROOT with the option disable-xft, recompile ROOT and recompile MEGAlib. As an alternative you can also comment out the line: gEnv-¿SetValue("X11.UseXft", "true"); in the file $NUSIM/src/main/src/NGlobal.cxx

Error message similar to:

```
Error in <TUnixSystem::DynamicPathName>: MathMore[.so | .sl | .dl | .a | .dll]
does not exist in <long list of paths>
Error in <ROOT::Math::IntegratorOneDim::CreateIntegrator>:
Error loading one dimensional GSL integrator
```

Something is wrong with your ROOT installation. Either you did not compile ROOTs MathMore library (did you say disable-mathmore during configuring ROOT?), or the MathMore library couldnt be compiled because GSL (GNU scientific library) isnt installed on your system. Either way make sure GSL is installed on your system and you have configured ROOT to compile MathMore. Fixing this requires a recompilation of ROOT.

Chapter 2

The Modules

2.1 Satellite super module

The satellite super-module (internally represented by the class NSatellite) provides an interface to all other satellite modules, which are required by various other simulation and analysis modules.

2.1.1 Orbit engine

The orbit engine provides information about the current orbit position of the satellite, e.g. altitude, inclination, position in TBD coordinates.

2.1.2 Pointing engine

The pointing engine provides the pointing of the focal plane module in declination and right ascension.

2.1.3 Orientation and alignment engine

2.1.4 Time engine

At the moment the time engine provides the absolute time of the satellite. Modules such as the detector module, the metrology and star tracker module derive their own time from this absolute satellite time and transfer it to the event, star tracker and metrology data sets.

Chapter 3

NuSIM Coordinate Systems Database

3.1 Purpose

The various components of NuSIM each operate in their own coordinate systems, and so in order to simulate the entirety of the spacecraft, it is necessary to keep track of the transformations between these systems. Furthermore, for many tests it is necessary to simulate NuSIM under changing conditions, and so for each timestep a set of coordinate system transformations must be provided.

3.1.1 List of Coordinate System Transformations

Name	Transformation
Inertial-SC	Inertial Frame to Spacecraft
SC-FB	Spacecraft to Focal Bench
FB-FP0	Focal Bench to First Focal Plane Module
FB-FP1	Focal Bench to Second Focal Plane Module
FB-MD0	Focal Bench to First Metrology Detector
FB-MD1	Focal Bench to Second Metrology Detector
FB-AS0	Focal Bench to First Aperture Stop
FB-AS1	Focal Bench to Second Aperture Stop
FB-OB	Focal Bench to Optics Bench (the mast)
OB-OM0	Optics Bench to First Optics Module
OB-OM1	Optics Bench to Second Optics Module
OB-ML0	Optics Bench to First Metrology Laser
OB-ML1	Optics Bench to Second Metrology Laser
OB-ST	Optics Bench to Star Tracker

3.2 Format

In order to provide NuSIM with a set of coordinate system transformations for each time step, a comma separated values (.csv) spreadsheet is used.

3.2.1 Layout

Each time-step is a pair of sequential rows: one for the translation between the coordinate systems, presented in (x, y, z), and the other for the rotation, presented as a quaternion, with the real component last: (q1, q2, q3, q4). Thus each coordinate system transformation is a set of four adjacent columns, and on the first row of each time-step the fourth column of each coordinate system transformation is empty.

There are several rows before the time-steps begin, representing header data at the top of the database file. These will include a row in which the name of each coordinate system transformation is in the first of the four columns its values occupy.

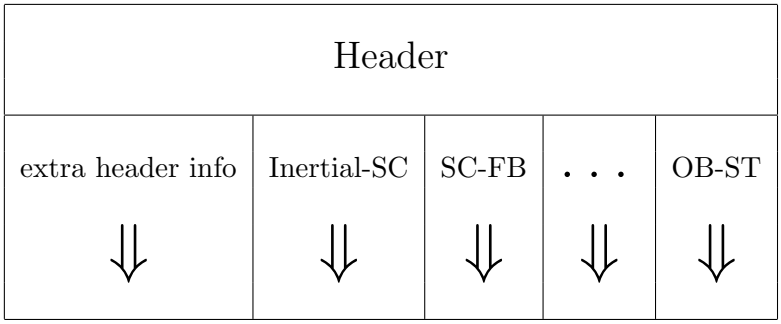
There are no rows between the time-steps, and no rows of interest after the time-steps.

3.2.2 Template

With each database format revision, a template file is produced, often in microsoft excel format. This file is simply a database with a single time-step: all the components in their ideal configuration. Historically, these file have been named along the lines of "NuSIM_OrientationsIDEAL_005.xls." Note that while Microsoft Excel's exported CSV files use carriage return ("\r") line-breaks, NuSIM requires its input databases to use newline ("\n") line-breaks.

3.2.3 Diagrams

File Layout



column layout

Section	Content			
Header	header info			
	Name			
	more header info			
Time-Step 0	x translation	y translation	z translation	
	q_1 (i coefficient)	q_2 (j coefficient)	q_3 (k coefficient)	q_4 (real)
Time-Step 1	x translation	y translation	z translation	
	q_1 (i coefficient)	q_2 (j coefficient)	q_3 (k coefficient)	q_4 (real)
Time-Step 2	x translation	y translation	z translation	
	q_1 (i coefficient)	q_2 (j coefficient)	q_3 (k coefficient)	q_4 (real)
⇓	⇓	⇓	⇓	⇓

3.3 NuSIM Database Transformer

NuSIM Database Transformer is a python library meant to simplify the process of generating multiple time-step databases with algorithmically generated coordinate system transformations. It takes as input the ideal template database (in csv format), and outputs sequential steps in accordance with an input function.

3.3.1 Requirements

NuSIM Database transformer is a Python script. That means it requires an installation of Python to run. Python comes standard on most modern Linux installations as well as OSX (although it may be in the developer tools, I don't recall), and is available free for most any operating system (even Windows) from python.org. To check to see if you have python, enter into a terminal:

```
python
```

If you find yourself in a python shell, you've got python. Exit with:

```
exit()
```

You do need to be able to program in Python to use NuSIM Database Transformer. Python is an interpreted language conforming to a number of common standards, which allows for mostly iterative programming with the ability to create functional (using functions themselves as variables) and object oriented programming. This readme talks

about python objects, functions, lambdas, tuples, lists, and dictionaries. Tutorials and explanations are available at python.org

NuSIM Database transformer requires an ideal database in CSV format. It assumes that this database contains the entries:

```
'Inertial-SC','SC-FB','FB-FPM0','FB-FPM1','FB-MD0','FB-MD1',
'FB-AS0','FB-AS1','FB-OB','OB-OM0','OB-OM1','OB-ML0','OB-ML1',
'OB-ST'
```

All on the same row, and that the last two rows with numbers in them are the ideal translational coordinates and the ideal rotational quaternians, respectively. Furthermore, it expects each transformation name listed above to share a column with the first of the three adjacent translational coordinates and the first of the four adjacent quaternion components (which are stored constant last, by the way). This is the standard format as found in ideal databases 005 and 006, and the database can handle any other extra columns, rows, or comments inserted into the ideal database as long as these rules are adhered to.

3.3.2 Description

NuSIM Databse Transformer is simply a python library containing useful tools for the generation of parametrically-changing databases for NuSIM. These are:

arcsecondsToRadians(asec)

returns asec, but in radians.

eulerAnglesToQuaternion(xrot, yrot, zrot)

Converts euler angles to quaternions via the formula from http://en.wikipedia.org/wiki/Conversion_between_quaternions_and_Euler_angles according to the x-y-z convention, which is the same as the formula from "Quaternions and Rotation Sequences" by Jack B. Kuipers, page 207, for converting Aerospace angle sequences to Quaternions. This means that what we are doing here is technically rotating about Z, then Y, then X. There is a small change in convention here; because we are doing a frame rotation, and not a point rotation, we are reversing the coefficient terms (hence the (-1.0)*), and we are putting the constant term last instead of first. It returns these as a tuple with four entries.

Class Output_Writer

A simple class which will either print or write to a file depending on what you want to do. If no filename, or a filename of None is input, .write() prints out (sans newlines or space each time), but if a filename is input, then .write() writes to that filename. close does nothing if you are printing out, but it closes the file if you're writing a file.

Database (described below) writes with one of these so it is possible to run a script that writes a database and pipe it somewhere instead of writing immediately to a file.

Class Entry

Each entry in the database needs a quaternion (.quater) with 4 entries and a set of coordinates (.coords) with three entries. These can be set directly be inputting a tuple into setCoords or setQuatr, or by inputing 3 numbers into setCoords and 4 into setQuatr. The inputs to the Constructor are the same as the inputs to setCoordsAndQuatr, which is to say either all three coords followed by all four entries of the quatr, or two tupples in a row. getX, getY, getZ, and getQ1, getQ2, getQ3, getQ4 are self explanatory keep in mind that the last entry of our quaternions is the constant term, (getQ4)

Class Database

This is the REALLY USEFUL ONE. This is a class designed to facilitate the creation of database files as input for NuSIM. This class takes as constructor input a filename of an ideal file.

After construction, a Database object has the following fields:

- newline: the newline character (either \n or \r which this should use when writing a .csv
- desiredColumns: the list of all the column names to use in this database
- header: the text part of the database above the timesteps
- columns: the dictionary of all the column names as keys for their x coordinate in the .csv
- ideal: the ideal Entry objects read form the ideal database (with column names as keys)
- current: the current Entry objects read form the ideal database (with column names as keys)
- previous: the previous Entry objects read form the ideal database (with column names as keys)
- idealCoordsLine: the coordinates line (split by ",") which was read from the ideal database
- idealQuaterLine: the quaternions line (split by ",") which was read from the ideal database
- step: the current timestep (starts at 0)
- out: the Output_Writer object with which to write out the .csv

This means that you can get, for example, the current X coord of FB-OB with:

```
database.current['FB-OB'].getX()
```

Writing functions:

- open(filename): this function sets this object to write at the given filename. It does this by setting self.out to be an Output_Writer(filename), so you can fail to put in a filename and write to standard out.
- close(): call this when this Database is done writing.
- writeHeader(): writes the self.header to out. Do this first when writing a database,
- writeStep() writes the current Step, exactly as formatted in idealCoordsLine and idealQuaterLine, but with the information from current, to out.
- newStep(stepFunc): This is the really important one. This function creates a new step, sets previous step to current step, and current to new step. There are two things you can enter into newStep:
  - any function with input (this database object) that outputs the next step If you input to newStep any function that returns a dictionary with valid Entry objects keyed to every entry of desiredColumns, when given this database object as input (as in, newStep calls stepFunc(self)), newStep will happily make the new Step the one setpFunc output.
  - any dictionary of functions which output entries keyed to any subset of desiredColumns for example, if I only wanted to play with FB-OB and SC-FB, I'd:

    ```
    database.newStep({
    'FB-OB':function_that_given_input_database_outputs_entry_for_FB-OB,
    'SC-FB':function_that_given_input_database_outputs_entry_for_SC-FB
    })
    ```

- writeDatabase(steps, stepFunc, output_filename): simply starts a database at output_filename, writes the header there, and writes steps Steps to The database, iterating each time with stepFunc, and then closes the database.

3.3.3 Use

To use NuSIM Database Transformer, a python script needs to import it as a library. Then it can use the tools listed above, which should be helpful in generating varying parameter databases for NuSIM.

The most useful single method of the library is: Database.writeDatabase(steps, stepFunc, output_filename).

To use this, create a database object (remember that the Database constructor takes as input the name of an ideal database CSV file), and then call the writeDatabase method from that object. The inputs should be:

- steps: the number of steps this database should have

- stepFunc: This can be either a function, which given a database object input, returns a dictionary with Entry objects keyed to each of: 'Inertial-SC','SC- FB','FB-FPM0','FB-FPM1','FB-MD0','FB-MD1','FB- AS0','FB-AS1', 'FB-OB','OB-OM0','OB-OM1','OB- ML0','OB-ML1', and 'OB-ST', or a dictionary containing a subset of the above keys, each keying to a function that takes a database object as input and returns an Entry object. This is the function with which the next step of the database will be computed at each step.

- output_filename: the name of the file you want to write this database to. This will be a csv file in the same format as the ideal file the Database object was created with. This can be NULL if you want to just print it.

Recall that python functions can be declared anonymously (inline) in the following format:

```
lambda inputs: output
```

Using this, it is possible to write a multi-step database in as little as one line of Python (although for readability this is inadvisable.

Remember that once a Database object has written, it increments its current step and resets its current and previous step entries. Therefore, writing multiple times from one Database object produces a continuation of the database, possibly with varying stepFunc entries, or multiple files. If you want to write multiple different databases from one ideal database, it is easiest to use the copy library, and after creating a database object from an ideal database, copy.deepcopy() it each time you want a database object to write with.

To run a python script you've written using this or any other library, call from a terminal:

```
python script.py
```

3.3.4 Examples

Note that readme_nusim_database_transformer.py is a text-only copy of this section of this document written as executable python. Running it will run all these examples.

Importing

The first step to using the NuSIM Database Transformer library is to import it. Python allows for

```
import nusim_database_transformer
```

but this would mean we'd have to type

```
nusim_database_transformer.
```

before everything we used that was defined in the library. For example, we'd have:

```
db = nusim_database_transformer.Database("ideal_file.csv")
```

This is a pain. Therefore we will simply import everything in the library into the script:

```
from nusim_database_transformer import *
```

Create a Database Object

Next we have to make a database object. Here it is important to choose the input file which is of the correct format. The one we've been using recently as of the time of this writing is called "NuSIM_OrientationsIDEAL_005.csv" And so we create a database object from that ideal file:

```
db = Database("NuSIM_OrientationsIDEAL_005.csv")
```

If at some future date, we wanted database files computed from the ideal database "NuSIM_OrientationsIDEAL_006.csv", we would simply have written:

```
db = Database("NuSIM_OrientationsIDEAL_006.csv")
```

instead, and that would have been the only difference in the script.

Simple Database

Now it is time to think about what we'd like to write to our output databases.

Consider the simplest case: a database consisting of all ideal entries. This allows for a simple illustration of the writeDatabase method.

The most powerful input for newStep or writeDatabase is stepFunc: any function, which given the entire database object, can manipulate that object and return a dictionary representing the next step, computed in any possible fashion.

The simplest possible value for stepFunc here would be a function that given an input database returned exactly the ideal step every time:

```
def simpleStepFunc(database):
      return database.ideal
```

Now, remember that a single database object should not be used to write more than one database file, as it will always write a continuation of the steps it has hitherto been writing (the step number always increments), so it is convenient, rather than generating a new database object each time we want to write a database, to copy the one we have, and write from the copy.

```
import copy
db2 = copy.deepcopy(db)
```

To write a database of 100 steps to the file "100_ideal_steps_A_005.csv", we'd call:

```
db2.writeDatabase(100, simpleStepFunc, "100_ideal_steps_A_005.csv")
```

Furthermore, recall that using inline functions, this can be done in fewer lines:

```
db3 = copy.deepcopy(db)
db3.writeDatabase(
            100, lambda database: database.ideal,
            "100_ideal_steps_B_005.csv"
            )
```

In addition, remember that it is also possible to substitute for stepFunc a dictionary of Entry - returning functions for each entry you want to vary with each step. The current step is initialized to be the ideal step, and so we, in effect, simply do not wish to vary any entries. We can therefore input for stepFunc an empty dictionary:

```
db4 = copy.deepcopy(db)
db4.writeDatabase(100, {}, "100_ideal_steps_C_005.csv")
```

Constant Offset

Now consider a slightly more complicated case: We want a database of 100 entries which are all the same, but not ideal. For example, consider the case where FB-OB is shifted along x by 5 mm. Here we need simply change the current step, and then print out 100 steps which are all unchanged from the current step. The clearest (if not the absolute shortest, codewise) way to accomplish this is:

```
db5 = copy.deepcopy(db)
db5.current['FB-OB'] = Entry(
                            db5.current['FB-OB'].getX() + 5,
                            db5.current['FB-OB'].getY(),
                            db5.current['FB-OB'].getZ(),
                            db5.current['FB-OB'].getQ1(),
                            db5.current['FB-OB'].getQ2(),
                            db5.current['FB-OB'].getQ3(),
                            db5.current['FB-OB'].getQ4()
                 )
db5.writeDatabase(100, {}, "100_FB-OB_x+5_A_005.csv")
```

Translations

Next, let's move on to somewhat more practical applications.

For example, consider shifting the x translation of FB-OB by 1 mm each step. You could add 1 to the current step each time:

```
def add1mmToX(database):
    return Entry(
                database.current['FB-OB'].getX() + 1.0,
                database.current['FB-OB'].getY(),
                database.current['FB-OB'].getZ(),
```

```
                database.current['FB-OB'].getQ1(),
                database.current['FB-OB'].getQ2(),
                database.current['FB-OB'].getQ3(),
                database.current['FB-OB'].getQ4()
            )

db6 = copy.deepcopy(db)
db6.writeDatabase(
                    100,
                    {
                        'FB-OB':add1mmToX
                    },
                    "100_FB-OB_x+n_A_005.csv"
                )
```

Rotations

Let's say you wanted to test how NuSIM reacts under various rotations about x, 0.1 arc seconds each step, between the optical bench and the focal bench, without any translation.

Recall than an Entry constructor can accept a pair of tuples, one for coordinates and one for quaternions.

```
def rotationsStepFunction(database):
    return Entry(
            database.current['FB-OB'].coords,
            eulerAnglesToQuaternion(
                                arcsecondsToRadians(0.1*database.step),
                                0.0,
                                0.0
                                )
             )

db7 = copy.deepcopy(db)
db7.writeDatabase(
                    100,
                    {
                        'FB-OB':rotationsStepFunction
                    },
                    "100_FB-OB_xrot+n_A_005.csv"
                )
```

3.4 Thermal Mast Bending

The document "Thermal_Distortion_2_for_JPL.xlsx" details the effects on the mast under the thermal effects of sunlight. In particular, it provides x and y offsets of the focal plane intersections with the beams from the optics, as well as $rotZ$, the twisting of the mast itself. These effects are most pronounced for a 170 degree angle of the mast toward the sun. To more fully model the effects of thermal mast bending on NuSTAR, a coordinate system transformation database had to be constructed for the mast in the configurations predicted for a full orbit.

3.4.1 Modeling the Mast as an Arc

The data given for mast distortions due to heating is given as a set of data points for different positions relative to the sun, with each point composed of the displacement of the beams from the optics modules at the focal bench, as well as the rotation (twist) of the mast itself.

I operated under the following assumptions:

- The twist in the mast is small enough that its effect on the bend of the mast is not worth calculating, which is to say it can be interpreted as one of the benches at either end having been rotated about the mast.
- The mast bend in x and y dimensions can be interpreted as separate arcs, and the displacement from each is additive, as the mast is square and is likely to bend more or less independently in each direction along these small angles.
- The beams from the optics modules are meant to move exactly parallel to the mast, centered at the center of the OM coordinate system. (supported by the coordinate systems IDEAL reference documentation).
- Over these small angles, second order approximations of cosine are acceptable.

First of all, I had to translate the coordinates given for the distortion of x and y along the rotated (by ROTZ) focal plane into distortions of x and y in a plane not rotated along z with respect to the optics modules.

This is most easily done by converting to radial coordinates with the center being the mast, and subtracting $ROTZ$ from the angle.

$$r = \sqrt{x^2 + y^2}$$

$$\theta = \arctan\left(\frac{x}{y}\right)$$

$$correctedY = r\sin\left(\theta - ROTZ\right)$$

$$correctedX = r\cos\left(\theta - ROTZ\right)$$

Now that those are corrected, we need to calculate the arc of the mast.

Let m be the length of the mast itself, which is mostly invariant, so we shall consider this to be the arc length. The arc angle θ and the arc radius r can be determined as follows:

The mast is essentially an arc (of radius r) with the optics module and the exact point on the focal plane meant to receive it each on what amount to beams perpendicular to the arc extending out by a distance x. Since the distortions in x and y are positive in all cases, we can assume the center of the arc is on the opposite side of NuSTAR from the $+X$ detector. Therefore the line from the center of the arc to the optics module emitting the beam (length $r+x$) is a leg of a right triangle, with the other leg being the beam itself and the hypotenuse being the line from the center of the arc to the point where the beam hits the detector (length $r + x + \Delta x$).

Mast Bending Model Diagram

Thus:

$$\cos(\theta) = \frac{r+x}{r+x+\Delta x}$$

A general rule of arcs is:

$$m = \theta r$$

So:

$$\cos(\theta) = \frac{\frac{m}{\theta}+x}{\frac{m}{\theta}+x+\Delta x}$$

This is not solvable analytically, (or at least Mathematica couldn't), so here we shift to a second order approximation of cos, which should be accurate for these small angles:

$$1 - \frac{\theta^2}{2} \approx \frac{\frac{m}{\theta}+x}{\frac{m}{\theta}+x+\Delta x}$$

For which the solutions for θ are:

$$\frac{-m \pm \sqrt{m^2 + 8x\Delta x + 8\Delta x^2}}{2(x+\Delta x)}$$

Given that when $\Delta x = 0$, $\theta = 0$, the correct solution is:

$$\frac{-m + \sqrt{m^2 + 8x\Delta x + 8\Delta x^2}}{2(x+\Delta x)}$$

Which does indeed grow as expected as Δx grows, so it seems a reasonable solution.

Given θ, and $r = \frac{m}{\theta}$, It should be clear that the optics bench will move by $r(1-\cos(\theta))$ along the x axis and $r\sin(\theta) - m$ along the z axis.

The optics bench itself, if we are looking at the arc with x translation, will rotate by θ about y.

The two dimension of bend (x and y) are essentially the same, and each is calculated as above, with their effects considered additive.

3.4.2 Implementation

A Coordinate System Transformation database was generated for each of the bent mast positions given by the original data using the NuSIM Database Transformer Python library. The function used to compute the transformation between the focal bench and the optical bench (the mast, "FB-OB") was as follows:

```
def compute_bent_mast_step(database):
    global thermals  # a list of (deltaX0, deltaY0, deltaX1, deltaY1,rotZ)
    x = database.ideal["OB-OM1"].getX()+database.ideal["FB-OB"].getX()
    y = database.ideal["OB-OM1"].getY()+database.ideal["FB-OB"].getY()
    rotZ = float(thermals[database.step][4])
    m=database.ideal["FB-OB"].getZ()+database.ideal["OB-OM1"].getZ()-
        database.ideal["FB-AS1"].getZ()
    deltaX = 25.4*thermals[database.step][0]
    deltaY = 25.4*thermals[database.step][1]
    rotR = math.sqrt((x**2) + (y**2))
    rotBase = math.atan(y/x)
    x = rotR*math.cos(rotBase - rotZ)
    y = rotR*math.sin(rotBase - rotZ)
    x_mast_arcangle = ((-1.0*m)+math.sqrt((m**2.0)+(8.0*x*deltaX)+
        (8.0*(deltaX**2.0))))/(2.0*(x+deltaX))
    x_mast_arcradius = m/x_mast_arcangle
    x_translation = x_mast_arcradius*(math.cos(x_mast_arcangle)-1.0)
    x_component_z_translation =
        (x_mast_arcradius*math.sin(x_mast_arcangle))-m
    y_mast_arcangle = ((-1.0*m)+math.sqrt((m**2.0)+(8.0*y*deltaY)+
        (8.0*(deltaY**2.0))))/(2.0*(y+deltaY))
    y_mast_arcradius = m/y_mast_arcangle
    y_translation = y_mast_arcradius*(math.cos(y_mast_arcangle)-1.0)
    y_component_z_translation =
        (y_mast_arcradius*math.sin(y_mast_arcangle))-m
    return Entry((
                    database.ideal["FB-OB"].getX() + x_translation,
                    database.ideal["FB-OB"].getY() + y_translation,
                    database.ideal["FB-OB"].getZ() +
                        x_component_z_translation +
                        y_component_z_translation
                ),
                    eulerAnglesToQuaternion(
                                        -y_mast_arcangle,
                                        x_mast_arcangle,
                                        rotZ
                                        )
                )
```

Chapter 4

The output file format keywords

Corresponds to NuSIM v0.9.0

Key:	SE
Parameters:	None
Description:	Indicates the start of a new event

Key:	TI
Parameters:	1: Time in seconds
Description:	The event time in seconds

Key:	ID
Parameters:	1: Number
Description:	A unique ID of the event

Key:	OG origin
Parameters:	1: Number (1: source, 2: background)
Description:	Tells if the origin of the photon is from a source or a background engine

Key:	TE
Parameters:	1: Number
Description:	The telescope ID. Either 1 or 2.

Key:	RD
Parameters:	1: Right ascension 2: Declination
Description:	The RA and DEC of the original photon empty of the photon was background.

Key:	OP original photon
Parameters:	1-3: Start position of the photon in the focal bench coordinate system in mm
Description:	4-6: Direction of the photon 7-9: Polarization of the photon 10: Energy of the photon in keV The initial parameters of the started photon ("original photon")

Key:	IP initial photon relative to the optics module
Parameters:	see OP
Description:	Contains the parameters of the photon when it is INTIALLY rotated and translated ointo the optics module.

Key:	CP current photon
Parameters:	see OP
Description:	The last parameters of the photon ("Current Photon"): If the pipeline is saved before the detector (interactions) engine, then the current photon parameters, if the event is saved after the detector (interactions) engine then the last photon parameters.

Key:	IA interaction
Parameters:	1: d or s: detector or shield 2: Telescope ID 3: Detector ID 4-6: Ideal position within the CZT detector in the CZT detectors coordinate system mm 7: Ideal energy in keV
Description:	Interactions as determined by the detector (interactions) engine.

Key:	PH pixel hit
Parameters:	1: Telescope ID 2: Detector ID 3: x pixel hit 4: y pixel hit 5: pre-trigger sample sum (pulse height) 6: post-trigger sample sum (pulse height) 7: ideal average depth (mm) 8: noised average depth (mm) 9: ideal energy deposit (keV) 10: noised energy deposit (keV)
Description:	A pixel hit, i.e. the detector effects engine applied to the ideal interactions

Key:	SH shield hit
Parameters:	1: Telescope ID 2: Detector ID 3: ideal energy deposit (keV) 4: noised energy deposit (keV)
Description:	A shield hit, i.e. the detector effects engine applied to the ideal interactions in the shield

Key:	NH nine-pixel hit
Parameters:	1: Telescope ID 2: Detector ID 3: x central pixel 4: y central pixel hit 5: pixel 1: pre-trigger sample sum (pulse height) 6: pixel 1: post-trigger sample sum (pulse height) 7: pixel 1: trigger (bool) 29: pixel 9: pre-trigger sample sum (pulse height) 30: pixel 9: post-trigger sample sum (pulse height) 31: pixel 9: trigger (bool) 32: ideal average depth (mm) 33: noised average depth (mm) 34: ideal energy deposit (keV) 35: noised energy deposit (keV)
Description:	A pixel hit, i.e. the detector effects engine applied to the ideal interactions

Key:	PE PHE data
Parameters:	TBD.
Description:	Not yet used

Keyword:	HT
Parameters:	1: Telescope ID 2: Detector ID 3-5: Position in the focal plane module (detector) coordinate system in mm 6-8: Position resolution of the above position in mm 9: Energy in keV 10: Energy resolution in keV 11: Observatory data: time in sec 12-14: Observatory data: direction of optical axis in inertial system 15-17: Observatory data: direction of event in inertial system 18-20: Observatory data: orientation of focal plane in optic bench system: translation 21-24: Observatory data: orientation of focal plane in optic bench system: quaternion 25-27: Observatory data: orientation of optic bench in inertial system: translation 28-31: Observatory data: orientation of optic bench in inertial system: quaternion
Description:	A reconstructed hit

Keyword:	OR the keyword is optional!
Parameters:	1-7: Space craft relative to inertial 8-14: Focal plane relative to space craft 14-21: Focal plane module 1 relative to focal plane 22-28: Focal plane module 2 relative to focal plane 29-35: Metrology detector 1 relative to focal plane 36-42: Metrology detector 2 relative to focal plane 43-49: Aperture 1 relative to focal plane 50-56: Aperture 2 relative to focal plane 57-63: Optical bench relative to focal plane 64-70: Optics module 1 relative to optical bench 71-77: Optics module 2 relative to optical bench 78-84: Metrology laser 1 relative to optical bench 85-91: Metrology laser 2 relative to optical bench 92-98: Star tracker 4 relative to optical bench
Description:	All orientations at event time