QuikSCAT Version 4 Geophysical Model Function Visualization Code

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Summary

This MATLAB code is designed to compute and plot the QuikSCAT Version 4 Geophysical Model Function (GMF) used for the processing QuikSCAT data into vector winds. The GMF computes the normalized radar cross-section (sigma-0) of the ocean's surface as a function of the 10 m near-surface neutral-stability wind speed and direction and the radar geometry and polarization. The code also illustrates how the GMF is inverted to infer the wind from multiple collocated sigma-0 measurements taken with different radar geometries and/or polarization.

Contents

Introduction

Historically, scatterometers have been used for measuring vector winds (Ulaby and Long, 2013). They do this indirectly by first measuring the normalized radar cross section (sigma-0) of a given patch of the ocean's surface from multiple geometries (azimuth angle, incidence angle, and/or polarization. Then, using a forward geophysical model function (GMF), which expresses sigma0 as a function of wind speed, wind direction, and the radar geometry, the near-surface vector wind is estimated from the sigma-0 measurements using maximum likelihood (ML) or least squares (LS) techniques via optimization of an objective function. Due shape of the GMF the wind estimate is not unique. Selection of a single estimate requires implementation of ambiguity selection algorithms, which are often ad hoc in nature, e.g., the median-filter based ambiguity selection used at JPL for SeaWinds,

QuikSCAT, and RapidScat data (Ulaby and Long, 2013; Hoffman and Leidner, 2005; Lungu and Callahan, 2006; Ricciardulli and Wentz, 2011; 2015; Fore et al., 2013).

The best Ku-band GMFs have been derived by collocating lots (millions) of sigma-0 measurements taken over a wide range of geometries with numerical weather prediction (NWP) surface winds (typically neutral-stability winds at 10 m) and computing histogram of sigma-0 versus wind. Each histogram bin is a narrow bin of relative azimuth/incidence angle and separate polarization that corresponds to a given geometry configuration. The average observed sigma-0 over all these collocations becomes the GMF. (Freilich and Dunbar 1993; Freilich 1996; Wentz and Smith 1999; Ricciardulli and Wentz, 2011; 2015).

SeaWinds on QuikSCAT

The SeaWinds on QuikSCAT scatterometer (typically referred to as QuikSCAT to differentiate it from SeaWinds on ADEOS and RapidScat) operated in wind observation mode from 1999 through 2009, with a few short data segments in later years. Its dual-pencil beam antenna rotates at 18 rpm about the nadir direction to sweep out a helical scan pattern, see Fig. 1. The inner beam measures sigma-0 at nominally 46.1° incidence while the outer beam measures sigma-0 at nominally 54° incidence. A given point in its 1800 km wide swath is observed up to 4 times. Over the1400 km wide inner swath, each point is observed 4 times, once by each beam looking forward and once for each beam looking backward. Over the outer swath, only two observations can be made, one looking forward for the outer beam, and the other looking backward. For more information on QuikSCAT and SeaWinds see (Freilich, 1996; Spencer et al., 2000; Lungu and Callahan, 2006; Ulaby and Long, 2013).

The QMOD4 GMF

The original Ku-band (13.4 GHz) GMF for QuikSCAT was based on the NSCAT1 GMF (Wentz and Smith 1999). The QSCAT-1 GMF developed by Freilich and Vanhoff (1999) was used in the operational processing of QuikSCAT wind retrievals at JPL and at NOAA until the deployment of the QMOD4 model function. The so-called QMOD4 is a QuikSCAT-specialized adaption of the Ricciardulli and Wentz (2011) GMF used by JPL for processing QuikSCAT data (Fore et al. 2013). The QMOD4 GMF is a tabular function written

Sigma-0 = QMOD4(*s, d, a, i*),

where *s* is the wind speed in m/s, *d* is the wind direction in deg relative to north in oceanographic (mass flow) convention, *a* is the radar observation azimuth angle in deg from the radar to the surface relative to north, and *i* is the observation incidence angle in deg. Note that because QMOD4 is specialized for QuikSCAT the radar polarization is coupled to the incidence angle so that there is no separate

polarization index. To be clear: 40° <= *i* < 50° is H-pol and 50° <= *i* <= 56° is V-pol. QuikSCAT's nominal indices angles are *i*=46.1° for the inner beam and *i*=54° for the outer beam. The wind speed quantized to 0.1 m/c over the range 0 <= s <= 50 m/s so there 501 table entries for speed. The incidence angle is quantized to 1° over the range 40° <= *i* <- 56° for 17 table entries. The wind direction *a* and radar azimuth *a* (both in deg relative to north) are combined to compute the relative azimuth angle *chi = d-a* mod 360 where *c* is quantized to 1° over 0 <= *c* <= 360 for a total of 361 table entries with *c*(360)=*c*(0). The GMF is periodic in *c*.
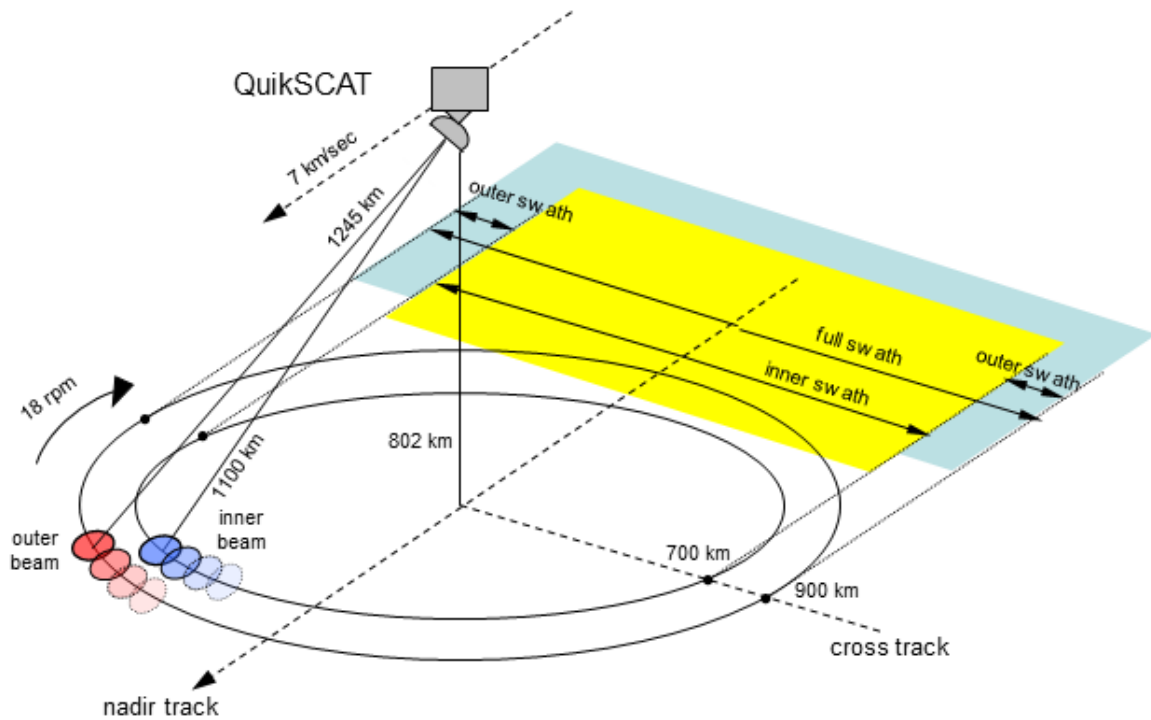

Figure 1. Illustration of the QuikSCAT observation geometry. The inner beam observations are made at a nominal incidence angle of 46.1° while the outer beam observations are made at 54°.

The GMF is multivalued, i.e., multiple geometry/vector wind values yield the same sigma-0 value. In particular, sigma-0 is a double cosine function of wind direction, resulting in a multi-valued inverse. To estimate the wind, multiple measurements of the same area (known as a 'wind vector cell' or wvc) are collected with different radar geometries. These are combined in the inversion. The purpose of this code is to help visualize how this works.

Given the multiple sigma-0 measurements at a given wvc, an objective function is formed and optimized. The objective function is best described as a weighted sum of the squared difference between the observed (measured) sigma-0 and the GMF-predicted sigma-0 based on an assumed wind speed and direction. The optimization choose the wind speed and direction that minimize the objective function, i.e.,

$$J(s,d) = \sum_{n=1}^{N} w(n)\left[z(n) - GMF(s,d,\mathrm{geom}(n))\right]^2$$

where J(*s,d*) is the objective function value for wind speed *s* and direction *d*. The sum is over the *N* measurements at the particular wvc, w(*n*) is the weighting factor (often the measurement variance predicted from the Kp equation, see below), z(*n*) is the *n*-th measurement, and GMF(*s,d*,geom(*n*)) is the sigma-0 value computed from the GMF evaluated at *s* and *d* for the radar geometry of the *n*-th measurement, i.e.,

GMF(*s,d*,geom(*n*)) = QMOD4(*s, d, a(n), i(n)*).

When LS is employed, w(*n*) is set to a constant. In maximum likelihood estimation, the objective function is the negative of the likelihood function which is computed as the sum of the weighted squared differences between the measurements and the GMF-predicted sigma-0. The weighting is variance of the measurement. This is computed based on the QuikSCAT processor design (Spencer et al., 2000; Lungu and Callahan, 2006). The QuikSCAT maximum-likelihood measurement variance w(*n*) can be expressed as

w(*n*)=[α(*n*) (1+K_{pm}) -1] GMF(*s,d*,geom(*n*))^2+β(*n*) GMF(*s,d*,geom(*n*)) (*n*)+ γ(*n*)

where α(*n*), β(*n*), and γ(*n*) are the QuikSCAT K_{pc} or communication noise parameters from the QuikSCAT L1B or L2A products, and K_{pm} is the assumed GMF variability (treated as a constant). The K_{pm} is accounts for the uncertainty or variability in creating the GMF. Typically, this is assumed to be 0.04 (Fore et al. 2013). The α(*n*), β(*n*), and γ(*n*) coefficients vary around the orbit with the measurement azimuth angle and beam. Representative values of these coefficients for the inner and outer beams are given by α=1.11, β=2e-4, and γ=1.3e7.

Ambiguity Selection

As noted, optimizing J(*s,d*) yields several possible local minimia, termed ambiguities. Any one of these may correspond to the true wind. There are from 1 to 4 ambiguities. A single solution is must be selected using ambiguity selection algorithm. QuikSCAT used a variation of the median-filter based algorithm developed for NSCAT by Schaffer et al. (1991) (Fore et al., 2013). Draper and Long (2002) estimated that ambiguity selection is accurate 95% of the time.

Rain

The QMOD4 GMF is only valid for non-raining conditions. Rain adversely affects the accuracy of the GMF by introducing attenuation of the radar signal due to propagation through failing rain and enhanced backscatter from the rain drops (Ulaby and Long, 2013). The net effect depends on both the rain rate and the surface

wind (Draper and Long., 2004b). In practice, rain-contaminated sigma-0 measurements are discarded in the QuikSCAT processing (Fore et al. 2013). The alternative is to simultaneously estimate both the rain rate and the surface wind (Draper and Long, 2004a).

Installing and running the code

This section illustrates how to install and run the code and provides sample outputs. Figure 2 shows a window from the default run of the code with Fig. 3 showing the corresponding text output.

To "install" the code, unzip the zip archive to the desired directory.
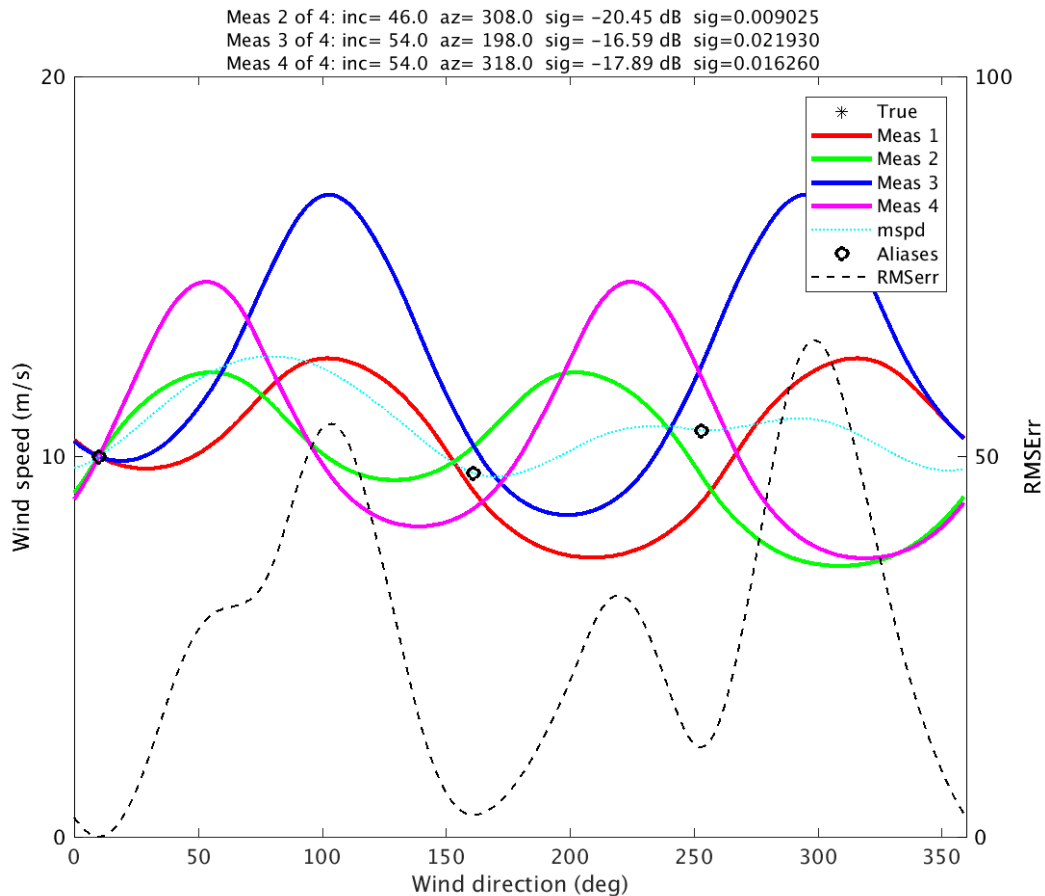
Figure 2. Graphics output from a default run of the Matlab script QMOD4plt.m for a 10 m/s wind blowing at 10 deg. Some of the descriptive title is clipped off the top. This case has three local minima or aliases.

To run the code, start Matlab and navigate to the install directory. Execute the Matlab script "QMOD4plt". A series of prompts are then provided that require user input, see Fig. 3. For a "default" run, at the "Enter true wind speed", enter 10 and hit return. Hit return for the remaining prompts until the graphics window appears. It

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should resemble Fig. 2. Different wind speeds (and directions) can be used to see the effect. At any prompt, a numerical value can be entered to override the default values.

The default is for a wvc in the QuikSCAT "sweetzone", which is in mid-swath away from the subsatellite point. Here there four measurements with a spread in azimuth angle. For the true 10 m/s, 0 deg wind, sigma-0 is computed using QMOD4 for each radar geometry. These are summarized in the text output and in the multi-line plot title. Then for each measurement, the code computes all possible wind speeds and directions that yield the same sigma-0 value using the associated radar geometry. These are plotted as the colored lines in Fig. 2. Note the double cosine wave. The curves exactly intersect at the true wind but nearly intersect at other directions. The objective function value as a function of direction is also plotted. There are three local minima that correspond to the ambiguities. The number of ambiguities and their directions varies with the true wind speed and direction and the geometry of the measurements. Why keep all the local minima and not just use the one with minimum value? To understand this, the variance of the measurements needs to be considered. This can be visualized by setting the SHOWBARS value to 1.

```
>> QMOD4plt
BYU QMOD4plt

Enter true wind speed: (m/s 10m neutral stability) 10
Enter true wind direction: (deg rel to north, oceanographic conven)
Enter number of sigma-0 measurements at wvc (1..4):
Enter measurement 1 of 4 incidence angle: (40-60 deg)
Enter measurement 1 of 4 radar azimuth angle: (0-360 deg)
Enter measurement 2 of 4 incidence angle: (40-60 deg)
Enter measurement 2 of 4 radar azimuth angle: (0-360 deg)
Enter measurement 3 of 4 incidence angle: (40-60 deg)
Enter measurement 3 of 4 radar azimuth angle: (0-360 deg)
Enter measurement 4 of 4 incidence angle: (40-60 deg)
Enter measurement 4 of 4 radar azimuth angle: (0-360 deg)

True wind:  10.00 m/s    10.00 deg
 Meas 1 of 4: inc= 46.00   az= 208.00   sig= -20.12 dB   sig=0.009721
 Meas 2 of 4: inc= 46.00   az= 308.00   sig= -20.45 dB   sig=0.009025
 Meas 3 of 4: inc= 54.00   az= 198.00   sig= -16.59 dB   sig=0.021930
 Meas 4 of 4: inc= 54.00   az= 318.00   sig= -17.89 dB   sig=0.016260
Number of Ambiguities: 3
 Ambiguity 1 of 4: dir=  10.00   spd= 10.00   ObjF=-0.000000
 Ambiguity 2 of 4: dir= 161.00   spd=  9.57   ObjF=-2.849000
 Ambiguity 3 of 4: dir= 253.00   spd= 10.70   ObjF=-11.773200

Enter true wind speed: (m/s 10m neutral stability) █
```

Figure 3. Text output from a default run of the Matlab script QMOD4plt.m for a 10 m/s wind blowing at 10 deg.

Editing the QMOD4plt.m file so that SHOWBARS=1 at the top will turn on the error bar plotting. Setting ENTERKP=1 at the top will allow the user to enter Kp coefficients rather than use the default values. Example outputs for the SHOWBARS=1 case using the default values are shown in Figs. 4 and 5. [Note that using SHOWBARS=1 calls the hatchfill.m routine, by Niel Tandon available from

Matlab Central at https://www.mathworks.com/matlabcentral/fileexchange/30733-hatchfill For user convenience, and as permitted by the hatchfill license, a copy of hatchfill.m is included in this code distribution.]
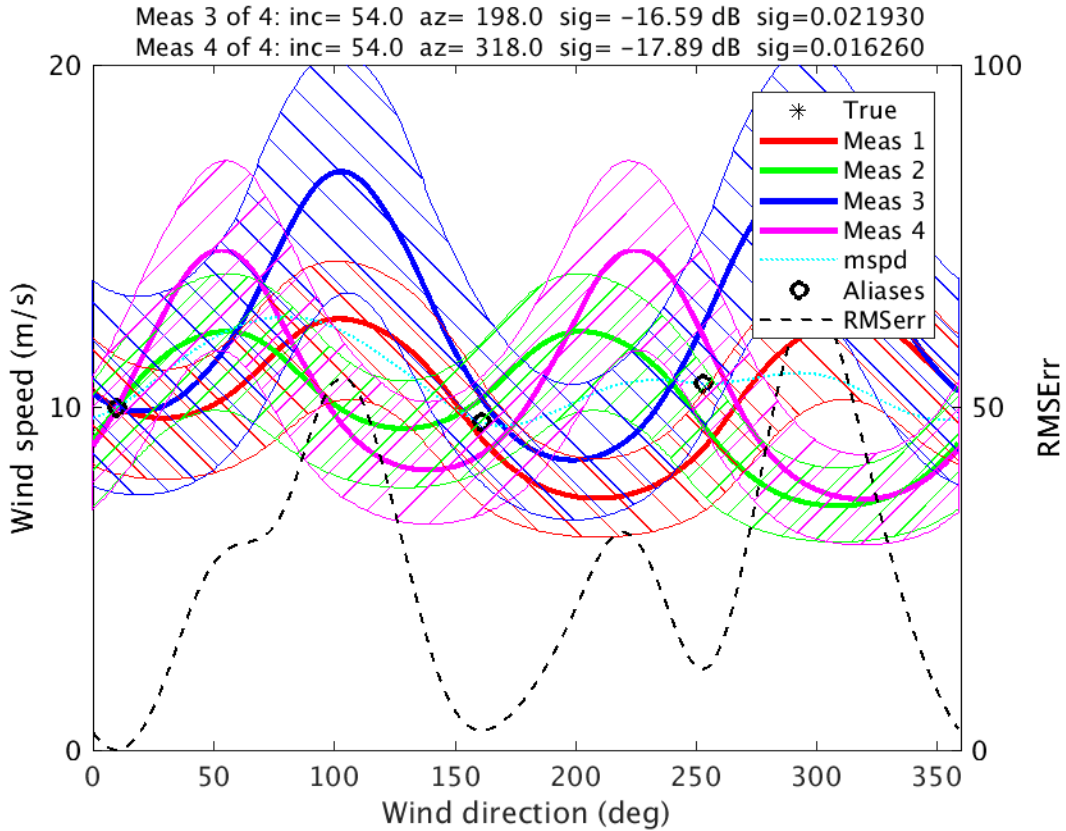

Figure 4. Graphics output from a default run of the Matlab script QMOD4plt.m for a 10 m/s wind blowing at 10 deg with SHOWBARS=1 set. Note the addition of the cross-hatched area which are +/- 1 sigma standard deviation (std) based on the radar measurement variance Kp equation (see text). The large std helps explain why all the local minima are kept rather than just the lowest value(s).This case produces three local minima or aliases. These wind speed and direction combinations "explain" the observed noisy sigma-0 values, i.e., are equally reasonable based on the measurements. Some of the descriptive title is clipped off the top.

The hatched regions in Fig. 4 show the +/- 1 standard deviation of the noise in sigma-0 measurements, which is significant compared to the variation (modulation) of sigma-0 with direction. Since the sigma-0 values of the ambiguities falling into the overlapping 1 sigma error bar regions, there is a possibility that the corresponding ambiguity is closer to the true wind that the ambiguity with the smallest objective function value. For this reason, all the local mins are retained and selection is done in a separate ambiguity selection algorithm. This approach has proven effective in enabling scatterometers to accurately measure global winds (Chang et al, 2009; Fore et al., 2013; Ricciardulli and Wentz, 2015).

```
>> QMOD4plt
BYU QMOD4plt

Enter true wind speed: (m/s 10m neutral stability) 10
Enter true wind direction: (deg rel to north, oceanographic convention)
Enter number of sigma-0 measurements at wvc (1..4):
Enter measurement 1 of 4 incidence angle: (40-60 deg)
Enter measurement 1 of 4 radar azimuth angle: (0-360 deg)
Enter measurement 2 of 4 incidence angle: (40-60 deg)
Enter measurement 2 of 4 radar azimuth angle: (0-360 deg)
Enter measurement 3 of 4 incidence angle: (40-60 deg)
Enter measurement 3 of 4 radar azimuth angle: (0-360 deg)
Enter measurement 4 of 4 incidence angle: (40-60 deg)
Enter measurement 4 of 4 radar azimuth angle: (0-360 deg)

True wind:  10.00 m/s   10.00 deg
 Meas 1 of 4: inc= 46.00  az= 208.00  sig= -20.12 dB  sig=0.009721
      alpha=1.110000  beta=0.000200  gamma=1.3e-07  std=0.003839
 Meas 2 of 4: inc= 46.00  az= 308.00  sig= -20.45 dB  sig=0.009025
      alpha=1.110000  beta=0.000200  gamma=1.3e-07  std=0.003567
 Meas 3 of 4: inc= 54.00  az= 198.00  sig= -16.59 dB  sig=0.021930
      alpha=1.110000  beta=0.000200  gamma=1.3e-07  std=0.008630
 Meas 4 of 4: inc= 54.00  az= 318.00  sig= -17.89 dB  sig=0.016260
      alpha=1.110000  beta=0.000200  gamma=1.3e-07  std=0.006403
Number of Ambiguities: 3
 Ambiguity 1 of 4: dir=  10.00  spd= 10.00  ObjF=-0.000000
 Ambiguity 2 of 4: dir= 161.00  spd=  9.57  ObjF=-2.849000
 Ambiguity 3 of 4: dir= 253.00  spd= 10.70  ObjF=-11.773200

Enter true wind speed: (m/s 10m neutral stability) █
```

Figure 5. Text output from a run of the Matlab script QMOD4plt.m for a 10 m/s wind blowing at 10 deg with SHOWBARS=1 set.

Code package listing

```
Matlab QuikSCAT Version 4 Geophysical Model Function Visualization Code
*************************************************************

Key files:

QMOD4plt.m : main code
QMOD4.pdf : documentation file
load_QMOD4.m : load QMOD4 into global memory
interp_QMOD4.m : evalute GMF for given wind speed and direction and
geometry
lookup_sigma0_QMOD4.m : given geometry and a sigma0 value "lookups" the set
                of wind directions and speed that yield same the sigma0
QS_MODLa004 : binary file containing tabular model function


Support files:

example.png : example output image (default run)
example2.png : example output image (default run with SHOWBARS=1 set)
hatchfill.m : copy of routine from Matlab Central (Neil Tandon 11 Jul 2011)
hatchfill_license.txt : copy of hatchfill.m license
license.txt : license for the general QMOD4 code package
myfigure.m : provides a useful alternative to the built-in figure command
            (can be deleted can calls to myfigure replaced by calls to
figure)
README.txt : this file
```

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