Accelerometer-Derived Atmospheric Density from the CHAMP and GRACE Satellites

Version 2.3

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Abstract

This report details the release of version 2.3 data for CHAMP and GRACE accelerometer-derived thermospheric total mass densities. The relevant references and updated procedures with respect to version 2.2 data are cited.

Description of Data

The CHAMP [Reigber et al., 2002] and GRACE [Tapley et al., 2004] satellites have provided useful data to the upper atmospheric and ionospheric scientific community since 2000 and 2002, respectively. The accelerometers onboard these satellites measure the vector quantity of acceleration caused by non-gravitational forces. After modeling and removal of the acceleration signals caused by solar radiation, Earth's albedo and infrared radiation, the drag acceleration, a_D, can be expressed in the direction of the satellite velocity with respect to the atmosphere, $\bar{v}$:

$$a_D = -\frac{1}{2}\rho C_D A_{ref} |\bar{v}|^2 \qquad (1)$$

where ρ is the total atmospheric density, C_D is the coefficient of drag and A_{ref} is the reference area of the satellite. Similarly, the lift acceleration, a_L, can be expressed in a direction perpendicular to $\bar{v}$ that depends on both the satellite geometry and the assumed drag/lift force model:

$$a_L = -\frac{1}{2}\rho C_L A_{ref} |\bar{v}|^2 \qquad (2)$$

where C_L is the coefficient of lift. These equations can be directly solved for atmospheric density, employing certain assumptions:

1. The measured acceleration contains only the signals related to atmospheric drag.
2. The coefficients of drag and lift can be modeled. The current version adheres to the method of Sutton [2009].
3. The reference area is known from knowledge of the satellite geometry and attitude.
4. Atmospheric winds are known or can be neglected.

In addition, an estimate of the error in density caused by our limited knowledge of the parameters in equations 1-2, as well as in the modeled accelerations caused by solar radiation pressure, Earth's albedo and infrared radiation, can readily be calculated. The uncertainty in density, u_ρ, can be expressed using the following formula:

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14. ABSTRACT
This report details the release of version 2.3 data for CHAMP and GRACE accelerometer-derived thermospheric total mass densities. The relevant references and updated procedures with respect to version 2.2 data are cited.

15. SUBJECT TERMS
accelerometer; density; neutral; atmosphere; thermosphere; ionosphere; space weather; drag coefficient; lift coefficient; CHAMP; GRACE; 2.3

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$$u_\rho = \sqrt{\sum_n \left(\frac{\partial \rho}{\partial x_i} u_{x_i}\right)^2} \tag{3}$$

where the x_i's are the n parameters introducing error into the measurement and the u_{x_i}'s are the estimated uncertainties of each parameter. In our analysis, the u_{x_i}'s are assumed to be uncorrelated. For more details on the data reduction and error analysis process see Sutton et al., 2007.

In an effort to reduce the size of the density data set without degrading the quality, the data has been binned and averaged along the satellite's orbit in 3-degree increments. As the sample size within a bin, n, increases, the constant systematic errors tend to average, while random errors tend to decrease in proportion to $1/\sqrt{n}$. This implies that it is possible to minimize the error of the averaged parameter by discriminating which data to include in the average. The algorithm responsible for this step automatically finds the optimal combination of data that minimizes the combined error of the averaging bin, and discards the rest. In practice, however, only a small percentage of density data was actually discarded.

In the event that binned and averaged data does not meet the requirements of your work, please contact Dr. Eric Sutton at "AFRL/RVBXI Org Mailbox <afrl.rvbxiorgmailbox@kirtland.af.mil>" to request higher resolution data (0.1 Hz for CHAMP and 0.2-1 Hz for GRACE).

Changes for Version 2.3

The major changes for this version are summarized here:

1. Extension of the data sets for CHAMP and GRACE.
2. The NRLMSIS model [Picone et al., 2002] is now run using $F_{10.7}$ and $\bar{F}_{10.7}$ values as measured at the surface of the Earth. Data prior to version 2.3 used $F_{10.7}$ and $\bar{F}_{10.7}$ values normalized to 1 AU which further complicated any data-model comparisons.
3. Computation of the quasi-dipole latitude, magnetic longitude, and magnetic local time was updated to the more compact and efficient routines given by Emmert et al. [2010].

Terms of Use

These data are processed and made publicly accessible as a service to the scientific community. Individuals planning scientific investigations with these data should contact Dr. Eric Sutton at "AFRL/RVBXI Org Mailbox <afrl.rvbxiorgmailbox@kirtland.af.mil>" to verify the status of possible new versions of the data, and to arrange coordination and/or collaboration with our ongoing scientific activities, as appropriate. Please reference the current document in all publications and presentations:

Sutton, E. K. (2011), Accelerometer-Derived Atmospheric Densities from the CHAMP and GRACE Accelerometers: Version 2.3, AFRL Technical Memo. DTIC# ADxxxxxx.

Future Plans

In future data versions, we plan to implement an updated method for modeling the drag and lift coefficients to account for shadowing of the neutral atmosphere by the satellite geometry and multiple reflections of atmospheric particles.

References

Emmert, J. T, A. D. Richmond, and D. P. Drob (2010), A Computationally Compact Representation of Magnetic Apex and Quasi-Dipole Coordinates with Smooth Base Vectors, J. Geophys. Res., 115(A08322), doi:10.1029/2010JA015326.

Picone, J. M., A. E. Hedin, D. P. Drob, and A. C. Aikin (2002), NRLMSISE-00 Empirical Model of the Atmosphere: Statistical Comparisons and Scientific Issues, J. Geophys. Res., 107(A12), 1468-1483, doi:10.1029/2002JA009430.

Reigber, C., H. Lühr, and P. Schwintzer (2002), CHAMP Mission Status, Adv. Space Res., 30(2), 129-134, doi:10.1016/S0273-1177(02)00276-4.

Sutton, E. K., R. S. Nerem, and J. M. Forbes (2007), Density and Winds in the Thermosphere Deduced from Accelerometer Data, J. Spacecraft and Rockets, 44(6), 1210-1219, doi:10.2514/1.28641.

Sutton, E. K. (2009), Normalized Force Coefficients for Satellites with Elongated Shapes, J. Spacecraft and Rockets, 46(1), 112-116, doi:10.2514/1.40940.

Tapley, B. D., S. Bettadpur, M. Watkins, and C. Reigber (2004), The Gravity Recovery and Climate Experiment: Mission Overview and Early Results, Geophys. Res. Lett., 30(L09607), doi:10.1029/2004GL019920.

Appendix A: Sample Plots

The following are sample time series plots of GRACE-B density and the corresponding NRLMSIS model density for 2009 and the first half of 2010:

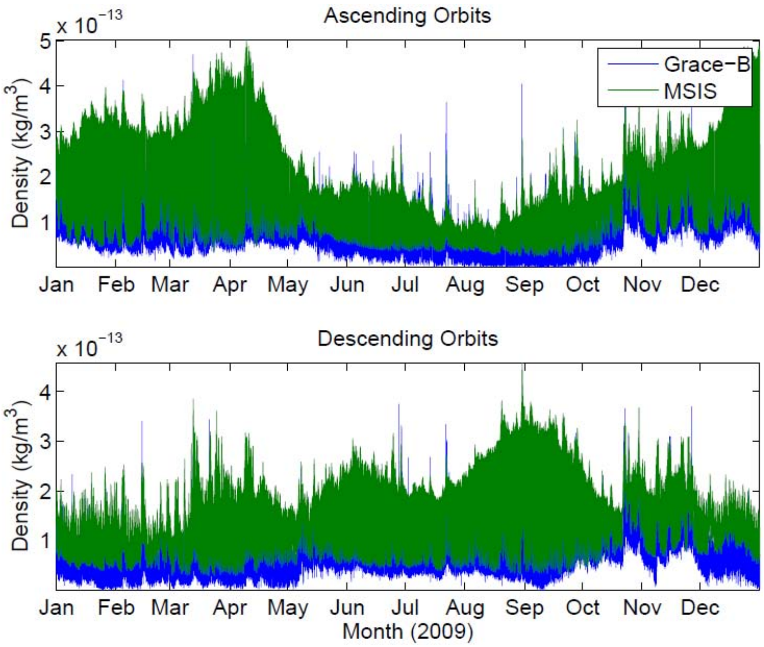

Figure 1: GRACE-B density (blue) and NRLMSIS (green) sampled on the satellite's orbit for 2009.

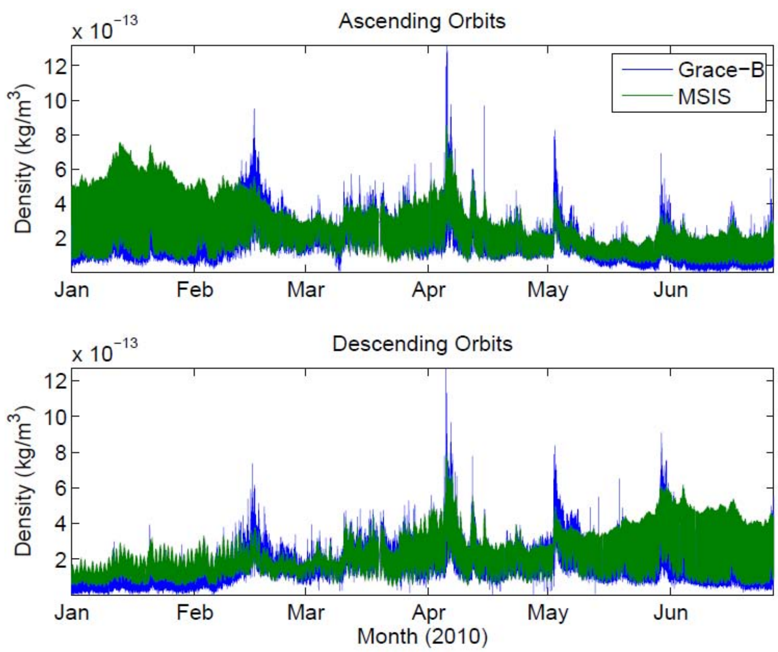

Figure 2: Same as figure 1, for the first half of 2010.

Appendix B: Example Ascii File Structure

```
Version 2.3; created by suttonek on 30-Nov-2010 21:14:56
Two-digit Year (years);Day of the Year (days);Second of the Day (GPS time,sec);Center Latitude of 3-degree Bin
(deg);Satellite Geodetic Latitude (deg);Satellite Longitude (deg);Satellite Height (km);Satellite Local Time
(hours);Satellite Quasi-Dipole Latitude (deg);Satellite Magnetic Longitude (deg);Satellite Magnetic Local Time
(hours);Neutral Density (kg/m^3);Neutral Density Normalized to 400km using NRLMSISe00;Neutral Density Normalized
to 410km using NRLMSISe00;NRLMSISe00 Neutral Density at Satellite Height;Uncertainty in Neutral Density
(kg/m^3);Number of Data Points in Current Averaging Bin;Number of Points in Current Averaging Bin that were
affected by Thrusters;Average Coefficient of Drag Used in Current Averaging Bin
10 177    10.00 -90 -88.99419  -63.98143 503.413 19.7332 -73.71119   16.49485 20.5873 7.108051e-14 5.098546e-13 4.105823e-13 9.019177e-14 3.860230e-15  3  0 3.567
10 177    23.33 -90 -88.84385  -18.88273 503.416 22.7435 -73.77020   19.37784 20.7837 7.097737e-14 5.097750e-13 4.111139e-13 9.498847e-14 3.858130e-15  3  1 3.556
10 177    47.50 -87 -87.64724   14.34620 503.392  0.9654 -73.77390   24.59991 21.1394 7.089113e-14 5.090842e-13 4.104115e-13 9.416610e-14 3.862704e-15  2  2 3.561
10 177    85.00 -84 -85.38886   26.54422 503.274  1.7891 -73.52399   32.52198 21.6793 7.166710e-14 5.142491e-13 4.143259e-13 9.302305e-14 3.937020e-15  1  1 3.569
10 177   162.50 -81 -80.55098   32.56386 502.721  2.2119 -72.14352   47.24453 22.6851 7.210448e-14 5.153559e-13 4.146200e-13 9.102788e-14 3.934854e-15  6  0 3.584
10 177   214.00 -78 -77.31195   33.89011 502.131  2.3146 -70.72843   55.38685 23.2441 6.515830e-14 4.636213e-13 3.725958e-13 8.989336e-14 3.625738e-15  5  0 3.554
10 177   250.00 -75 -75.04370   34.42544 501.615  2.3603 -69.57310   60.29750 23.5828 6.212690e-14 4.402328e-13 3.535183e-13 8.916081e-14 3.469878e-15  9  0 3.528
10 177   300.00 -72 -71.88975   34.88957 500.764  2.4051 -67.80791   66.17679 23.9904 5.887052e-14 4.141842e-13 3.322204e-13 8.820172e-14 3.327229e-15  9  0 3.495
10 177   347.50 -69 -68.89044   35.14952 499.815  2.4357 -66.01116   70.91245  0.3211 5.725469e-14 3.994563e-13 3.200514e-13 8.733658e-14 3.266365e-15  8  0 3.459
10 177   392.50 -66 -66.04656   35.29419 498.798  2.4578 -64.23829   74.78696  0.5935 5.472762e-14 3.782755e-13 3.027602e-13 8.655030e-14 3.141633e-15 10  0 3.425
10 177   440.00 -63 -63.04223   35.37486 497.607  2.4764 -62.31757   78.36586  0.8471 5.472776e-14 3.740401e-13 2.990373e-13 8.575618e-14 3.149964e-15  9  0 3.391
10 177   497.50 -60 -59.40206   35.40426 496.019  2.4943 -59.94606   82.15424  1.1177 5.220283e-14 3.513384e-13 2.805144e-13 8.486031e-14 3.053279e-15  6  0 3.351
10 177   535.00 -57 -57.02601   35.39422 494.905  2.5041 -58.37744   84.37216  1.2774 5.160748e-14 3.435582e-13 2.740690e-13 8.432946e-14 2.998837e-15  9  0 3.331
------------------------------
---- 1843 Lines Not Shown ----
------------------------------
10 177 85897.50  -3  -2.03912   40.08625 465.171  2.5287 -10.86710  113.14250  2.8705 5.774891e-14 2.616695e-13 2.059126e-13 1.099009e-13 3.289992e-15  4  0 2.865
10 177 85934.17   0   0.31897   39.97335 464.313  2.5313  -8.33138  113.15544  2.8828 5.492340e-14 2.456696e-13 1.931637e-13 1.099238e-13 3.146030e-15  6  0 2.857
10 177 85985.00   3   3.58904   39.81690 463.224  2.5350  -4.79005  113.10157  2.8951 5.272951e-14 2.321755e-13 1.823306e-13 1.092631e-13 3.049638e-15  4  0 2.846
10 177 86037.50   6   6.96718   39.65576 462.228  2.5389  -1.10935  112.97285  2.9029 5.043097e-14 2.190352e-13 1.717852e-13 1.078722e-13 2.941714e-15  4  0 2.840
10 177 86075.00   9   9.38049   39.54115 461.597  2.5416   1.52951  112.84460  2.9061 4.742164e-14 2.042500e-13 1.600410e-13 1.065679e-13 2.805641e-15  4  0 2.837
10 177 86097.50  12  10.82857   39.47267 461.250  2.5433   3.11540  112.75604  2.9072 4.851799e-14 2.080318e-13 1.629176e-13 1.057134e-13 2.874003e-15  2  0 2.835
10 177 86162.50  15  15.01202   39.27634 460.383  2.5483   7.70243  112.46505  2.9082 5.313021e-14 2.252150e-13 1.761382e-13 1.032358e-13 3.086137e-15  2  2 2.835
10 177 86225.00  18  19.03435   39.09039 459.735  2.5532  12.11338  112.15878  2.9073 4.966526e-14 2.084956e-13 1.629274e-13 1.013548e-13 2.920167e-15  3  0 2.839
10 177 86242.50  21  20.16050   39.03895 459.584  2.5547  13.34746  112.07222  2.9071 4.928709e-14 2.063579e-13 1.612379e-13 1.010017e-13 2.896263e-15  4  0 2.841
10 177 86309.17  24  24.44990   38.84606 459.134  2.5603  18.04157  111.75449  2.9068 4.281129e-14 1.773611e-13 1.385968e-13 1.006618e-13 2.608541e-15  6  0 2.844
10 177 86335.00  27  26.11168   38.77285 459.009  2.5626  19.85662  111.64132  2.9073 4.261275e-14 1.757480e-13 1.373793e-13 1.010458e-13 2.633609e-15  3  0 2.843
10 177 86385.00  30  29.32731   38.63407 458.840  2.5673  23.36192  111.44787  2.9101 5.680612e-14 2.320233e-13 1.815635e-13 1.027581e-13 3.357270e-15  2  2 2.848
```

Appendix C: Support Files

In addition to this document, two support text files accompany the data. The 'HISTORY.density.v2.3.txt' file outlines the changes that have been made to the processing routines from version to version. The 'README.density.v2.3.txt' gives instructions for acquiring this data and interpreting the data format.

History File:

```
--------------------------------------
Changes for Version 2.0 CHAMP Density:
--------------------------------------
1. Interpolation of satellite attitude data improved
      a. methods updated to handle missing data
      b. index (NumInterp variable) added to data set indicating any
         interpolation of attitude data
2. Accelerometer instrument biases reprocessed and smoothed
3. Coefficient of drag updated from method of Cook [1965] to Sentman [1961]
      a. includes more realistic formulation of the coefficient of drag
      b. includes the effect of thermal drag, which increases the coefficient
         of drag for long satellites
      See:  Sutton, E. K. (2009), Normalized Force Coefficients for
            Satellites with Elongated Shapes, J. Spacecraft and Rockets,
            46(1), 112-116, doi:10.2514/1.40940.
      c. Variable 'Cd' added
4. Variable 'LatBin' added and 'Lat' modified
      a. LatBin gives the center of the current averaging bin
      b. Lat gives the mean position of the satellite at data points within
         the current averaging bin
      c. This ensures that the satellite position (defined by variables Lat,
         Lon, and Height) is consistent
5. NRL-MSIS model density is given at each time and satellite position
--------------------------------------
--------------------------------------
Changes for Version 2.1 CHAMP Density:
--------------------------------------
1. Addition of Quasi-Dipole Latitude (Mlat), Magnetic Longitude (Mlon), and
   Magnetic Local Time (Mlt)
      See:  Richmond, A. D. (1995), Ionospheric Electrodynamics Using
                  Magnetic Apex Coordinates, J. Geomag. Geoelectr., 47(2),
                  191-212.
--------------------------------------
--------------------------------------
Changes for Version 2.2 CHAMP and GRACE Density:
--------------------------------------
1. First Version for GRACE Density, everything conforms to version 2.2 of
   CHAMP density
--------------------------------------
--------------------------------------
Changes for Version 2.3 CHAMP and GRACE Density:
--------------------------------------
1. NRL-MSIS density values updated
      a. now using observed F10.7 values in place of 1 AU normalized values
      b. corrected Ap/ap/F10.7 indices used during the first couple data
         points of the day
2. Software update for computation of Quasi-Dipole Latitude, Magnetic
   Longitude, and Magnetic Local Time
      See:  Emmert, J. T., A. D. Richmond, and D. P. Drob (2010), A
```

computationally compact representation of Magnetic Apex and Quasi Dipole coordinates with smoothe base vectors, J. Geophys. Res., 115, A08322, doi:10.1029/2010JA15326.

Readme File:

%%%% Format Description:

All Density data has been averaged into 3-degree latitudinal bins to conserve space and reduce any random errors. The bins are centered around lat = [-90:3:90] deg, omitting any values for which there are 0 data points in the averaging bin. Neutral density has also been normalized to 2 heights (400km and 410km) using the NRL-MSISe-00 Empirical Density Model.

%%%% Ascii Format:

Ascii files are arranged in columnn format with a 2-line header of Version Information and Descriptions of each field (including units used) separated by semi-colons (;). The length of each file is approximately 1840 lines.

Column:	Format:	Description:	Units:
[1-2]	2I	Two-digit Year	years
[4-6]	3I	Day of the Year	days
[8-15]	8.3F	Second of the Day GPS time	sec
[17-19]	3I	Latitude Center of Current Averaging Bin	deg
[21-29]	9.5F	Geodetic Latitude	deg
[31-40]	10.5F	Longitude	deg
[42-48]	7.3F	Satellite Height	km
[50-56]	7.4F	Satellite Local Time	hours
[58-66]	9.5F	Quasi-Dipole Latitude	deg
[68-77]	10.5F	Magnetic Longitude	deg
[79-85]	7.4F	Magnetic Local Time	hours
[87-98]	12.6E	Neutral Density	kg/m^3
[100-111]	12.6E	Density @ 400km	kg/m^3
[113-124]	12.6E	Density @ 410km	kg/m^3
[126-137]	12.6E	NRL-MSIS Density at Satellite Height	kg/m^3
[139-150]	12.6E	Density Uncertainty	kg/m^3
[152-153]	2I	Number of Data Points in Current Averaging Bin	
[155-156]	2I	Number of Points that Require Interpolation	
[158-162]	5.3F	Coefficient of Drag Averaged over Bin	

%%%% Matlab and Netcdf Format:

Matlab and Netcdf formats are identical. The variables below are structure arrays containing '.data', '.units', and '.long_name'. For most of the variables, the size of the '.data' structure is n by 1, where n is approximately 1840.

Variable Name:	Size:	.long_name:	.units:
Year.data	1x1	Two-digit Year	years
Doy.data	1x1	Day of the Year	days
Sec.data	nx1	Second of the Day GPS time,	sec
LatBin.data	nx1	Latitude Center of Current Averaging Bin	deg
Lat.data	nx1	Geodetic Latitude	deg
Lon.data	nx1	Longitude	deg
Height.data	nx1	Satellite Height	km
LocTim.data	nx1	Satellite Local Time	hours
Mlat.data	nx1	Quasi-Dipole Latitude	deg
Mlon.data	nx1	Magnetic Longitude	deg
Mlt.data	nx1	Magnetic Local Time	hours
Density.data	nx1	Neutral Density	kg/m^3
D400.data	nx1	Density @ 400km	kg/m^3
D410.data	nx1	Density @ 410km	kg/m^3
Dmsis.data	nx1	NRL-MSIS Density at Satellite Position	kg/m^3
U_wy.data	nx1	Uncertainty	kg/m^3
Num.data	nx1	Number of Data Points in Current Averaging Bin	
NumInterp.data	nx1	Number of Points that Require Interpolation	
Cd.data	nx1	Coefficient of Drag Averaged over Bin	

%%

These data are process and made publicly-accessible as a service to the scientific community. Individuals planning scientific investigations with these data should contact Dr. Eric Sutton at "AFRL/RVBXI Org Mailbox <afrl.rvbxiorgmailbox@kirtland.af.mil>" to verify the status of possible new versions of the data, and to arrange coordination and/or collaboration with our ongoing scientific activities, as appropriate.

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