IGRF-13 DGRF2015/IGRF2020/PGRF2025 CANDIDATE MODELS SUBMITTED BY NASA/GSFC

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1. Information about the candidate models

We preface the following information by stating the the DGRF2015 and IGRF2020 NASA/GSFC candidates were derived from a more sophisticated Comprehensive Model, CM6, based upon CHAMP, Ørsted, SAC-C, and Swarm satellite data and ground observatory data spanning 1999 to mid-2019. The DGRF2015 was simply extracted while the IGRF2020 was extrapolated from CM6. Therefore, the following information reflects the properties of the CM6 parent model.

(1) **Which satellite, observatory and/or repeat station data sets were used?**

Satellite scalar data and scalar along track differences from the Ørsted, CHAMP, SAC-C, and Swarm missions all with 30 second sampling were used; along-track differences are computed from samples 15 seconds apart. We used Ørsted data from the period 15 March, 1999 through 23 February, 2011, CHAMP data from the period 30 June, 2000 through 4 September, 2010, SAC-C data from the period 23 January, 2001 through 4 December, 2004, and Swarm data from the period 25 November, 2013 through 31 December, 2018.

Vector data and along track vector differences from the CHAMP and Swarm missions for the same periods were also used at a sampling rate of 30 seconds; along track vector differences, computed from samples 15 seconds apart, were used for both missions – four satellites in all. From the two side-by-side flying Swarm *Alpha* and *Charlie* satellites cross track scalar and vector differences were used from the period 17 April, 2014 through 31 December, 2018, at a sampling rate of 30 seconds. Cross track differences were computed from data where *Alpha* and *Charlie* were nearest in geocentric latitude at a temporal separation of at most 15 seconds (typically $4--10$ seconds apart).

Ground observatory data hourly-mean (OHM) values from 199 ground observatories were used from the period January 1999 through April 2019. These data were checked and cleaned for trends, spikes and other errors *(Macmillan, S. and Olsen, N. (*2013*). Observatory data and the Swarm mission. Earth, Planets and Space,* $65:1355-1362$*).*

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(2) **What were the data selection and rejection criteria?**

The data selection criteria were the following: (1) $Kp \leq 2^{-}$ (3^{0} for differences); (2) $dDst/dt \leq 3$ nT/hr (for regular and difference data); (3) Non-differenced satellite vector and scalar data only from dark regions, i.e. sun at least 10° below the horizon; (4) Satellite vector data equator-ward of 55° quasi-dipole (QD) latitude; (5) Vector difference data from CHAMP mission were used when both double and single Star Tracker heads were available for attitude determination; and (5) Swarm data diverging from the CHAOS-6 x7 model by more than 100 nT in the scalar field or 500 nT in any of the vector field components were rejected.

Data rejection takes place at each iteration through the identification and elimination of gross outliers as determined by an inspection of residual plots.

(3) **What weights were allocated to the different kinds of data?**

Vector OHM data at all local times and latitudes were used and if poleward of $\pm 55°$ QD latitude were assigned isotropic sigmas of 15 nT, while those equatorward of $\pm 10°$ were assigned isotropic sigmas of 7 nT, and elsewhere isotropic sigmas of 4 nT.

Scalar data from the nightside at all latitudes from Ørsted and SAC-C were used and these were given sigmas of 4 nT. Scalar sums and differences from all local times and latitudes were used with the same weighting.

When two Star Tracker heads are available on CHAMP we use scalar data from the nightside at all latitudes and vector data from the nightside at low-mid latitudes. Sigmas of 3 nT are used for scalar data and the vector isotropic factor. Attitude error is included using 10 arcsec pointing and rotation angle sigmas. Scalar norht-south sums and differences are used at all local times at all latitudes and vector north-south sums and differences are used at low-mid latitudes at all local times. The sums are assigned a 3 nT sigma isotropic error while differences use 0.3 nT and both use the same attitude error just mentioned. When only one Star Tracker head is available on CHAMP we use only vector data from the nightside at low-mid latitudes and north-south vector sums and differences at low-mid latitudes at all local times. The same sigma assignments are used for single heads except that the attitude error is now comprised of 10 arcsec pointing and 40 arcsec rotation angle sigmas.

Data from Swarm *Alpha*, *Bravo*, and *Charlie* was selected in exactly the same way as the dual-head Star Tracker CHAMP data. However, assigned sigmas differ in that 2.2 nT is used for scalar and vector data components and attitude error is not considered. The north-south sums are assigned a 2.2 nT sigma per component while differences use 0.3 nT. The east-west vector sums and differences from *Alpha* and *Charlie* are from low-mid latitudes and all local times, while the scalar components are from all latitudes. They too are assigned a 2.2 nT sigma per component for sums while differences use 0.3 nT.

All data were weighted by $\sin\theta$, where θ is their respective geographic colatitude, in order to mitigate high-density data in the polar regions.

Robust estimation was employed via Iteratively Reweighted Least-Squares (IRLS) using Huber weighting and so for the ith iteration, if the kth residual, $e_{i,k}$, was within $c = 1.5$ sigma of its respective distribution,σ_i, then it was treated as Gaussian noise with the previous uncertainty assignment. However, if it was outside of $c = 1.5$ sigma of the mean, then it was treated as Laplacian noise. Thus, weights were assigned according to

$$w_{i,k} = \frac{1}{\sigma_i^2} \min\left(\frac{c\sigma_i}{|e_{i,k}|}, 1\right). \tag{1}$$

(4) **Were data weighted for equal spatial or temporal coverage?**

All data were weighted by $\sin\theta$, where θ is their respective geographic colatitude, in order to mitigate high-density data in the polar regions.

(5) **How was the forward extrapolation to 2020.0 carried out?**

Because Swarm data was selected only through 31 December, 2018, the IGRF2020 was derived from a simple linear extrapolation passing through the CM6 Gauss coefficients at 2018.75 and 2019.0, and likewise, the formal error-covariance was extrapolated to 2020.0.

(6) **How is the average secular variation from 2020.0 to 2025.0 predicted? Was the secular variation at 2020 taken, or was it forward extrapolated?**

The GSFC candidate model for the average SV from 2020.0 to 2025.0 are made with the geomagnetic data assimilation system (called GEMS) developed in GSFC. To make the prediction, we utilized the gauss coefficients from paleomagnetic and geomagnetic field models as the observations, and our Boussinesq geodynamo model as the dynamics model for the data assimilation. Specifically, cals3k paleomagnetic model is used from 10CE to 1590CE; gufm1 from 1590 to 1960, CM4 from 1960 to 2001, and CM6 (see explanations on PGRF and IGRF candidate model sections) for 2001 to 2019. In our dynamo model, we used the magnetic Rossby number R_o and the Ekman number E: $R_o = E = 1.25 \times 10^{-6}$, with the numerical resolution of $84 \times 84 \times 132$.

Our data assimilation algorithm is based on the Kalman Filter scheme with 400 ensemble, in which the forecast x^f and the observation y are used to make the analysis x^a at the analysis time τ_a via

$$x^a = x^f + \frac{P^f H^T}{HP^f H^T + R}\left(y - Hx^f\right), \tag{2}$$

where P^f is the covariance matrix of the forecast ensemble, H is the observation operator, and R is the observation error covariance. The analysis x^a are then used as the initial conditions for prediction up to the next analysis time, i.e. the entire analysis cycle (defined as the difference between two adjacent analysis time). The initial 400 ensemble members are selected randomly from our dynamo simulation solution database, with any two solutions separated by at least 10% magnetic free-decay time (which is approximately 2000 years for the Earth's core). The analysis cycle is set to be 20 years before 2000, 5 years from 2000 to 2015, and 1 year after 2015.

We made three different 6−year forecast series: one for 2017 − 2023, one for 2018 − 2024, and one for 2019 − 2025. Our forecasts are made for the scaled gauss coefficients $G_{nm} = g_{nm}/g_{10}$, $H_{nm} = h_{nm}/g_{10}$, where n is the degree and m is the order. The ensemble-mean forecast and the standard deviation

$$\overline{x}^f = \frac{1}{N_f}\sum_{i=1}^{N_f} x_i^f, \qquad \sigma^f = \left[\frac{1}{N_f}\sum_{i=1}^{N_f}\left(x_i^f - \overline{x}^f\right)^2\right]^{1/2} \tag{3}$$

(where N_f is the ensemble size) are used for our forecasts and uncertainties. We first calculate the annual SV from 2019 to 2025. They are then used to calculate the gauss coefficients (g_{nm}, h_{nm}) in 2025. In this process we also use the axial dipole (g_{10}) and its time derivative ($\dot{g}_{10}$) in 2019 to determine the forecast coefficients. Our average SV coefficients are then obtained by the difference between the forecast gauss coefficients in 2025 and the gauss coefficients in 2019 from CM6, and are validated with our IGRF2020 gauss coefficients. The final estimated uncertainties are the average σ^f of the 6-year forecast period.

We should point out that the uncertainties derived from our forecast ensemble covariance matrices do not directly include any bias nor uncertainties from geomagnetic models, although the estimated observation error covariance R are used in deriving the analysis x^a. For example, CM6 removes much of the contributions from ionospheric currents, which is necessary for our data assimilation system and therefore SV forecasts. But it may create bias with IGRF definitions.

(7) **If iterating the Least Squares process, what starting model used, and how many iterations were needed?**

The CIY4 model of *Sabaka et al., (2018)*, based upon the first four years of Swarm data, was updated to the CIY5 model by adding the fifth year of Swarm data. The CIY5 was used to initialize all of the model parameters with the exception of the core field before 2013.9 and the CHAMP vector magnetometer alignment angles. The CHAOS-6-x8 model was used to initialize the core field from 1999 to 2013.9. The CHAMP alignment angles were initialized to zero. Four iterations were required for convergence.

(8) **If scalar data were used that required linearization of the inversion, what starting model used, and how many iterations were needed?**

Because we are using a gradient-based estimator, the scalar data were linearized with respect to the current model of the current iteration described in the previous answer.

(9) **What, if any, regularization was used, e.g., use of an a-priori model with specified (co-) variance, or addition of some quadratic penalty function to the sum square deviation?**

Because this model is extracted from a Comprehensive Model (CM6), several regularization terms were used. However, for the core secular variation we minimized the mean-square $\dddot{B}_r$ component over the core-mantle boundary through time. This was a smoothing norm so the preferred state for this norm was zero.

(10) **What, if any, sources were co-estimated and removed? Were any a-priori models or information used in the co-estimation (for instance mantle conductivity models in the estimation of induced magnetospheric and/or ionospheric fields)?**

CM6 co-estimates the core field, crustal field, ionospheric field and associated induced field, magnetospheric field and associated induced field, oceanic M2, N2, and O1 tidal fields, OHM biases, and vector magnetometer alignment angles through time for the CHAMP and Swarm vector data.

In addition, Selective Infinite Variance Weighting (SIVW) was used to mitigate biases in the core, crustal, and tidal fields when different combinations of dayside and disturbed data are used and follows the scheme of *Sabaka et al., (2018)*.

We use an *a priori* conductivity model for ionospheric induction that comes from a "1-D plus Oceans" treatment of the conducting layers, and has been adopted by the Swarm mission. That is, an upper layer that considers oceans and conductive sediments versus continents with a 1-dimensional radially varying conductivity profile below this.

(11) **What was the method used to solve the Least Squares equations?**

We use IRLS with Gauss-Newton (GN) steps which includes quadratic and linear-equality constraints. These steps are carried out directly on the normal equations.

(12) **What was the fit to the data?**

Table 1. CM6 weighted residual statistics for Ørsted and SAC-C.

Name	Lat.	Sun	Comp.	N	Mean	RMS
Ørsted	low	dark	F	169,861	-0.45	2.34
	mid	dark	F	751,943	0.82	2.08
	high	dark	F	427,860	1.14	3.95
	low	light	$NSDF$	277,662	0.00	0.51
			$NSSF$	277,662	3.52	8.05
	low	dark	$NSDF$	251,673	0.00	0.38
			$NSSF$	251,673	-1.00	5.20
	mid	light	$NSDF$	1,376,911	0.00	0.51
			$NSSF$	1,376,911	0.56	5.69
	mid	dark	$NSDF$	1,113,677	-0.00	0.51
			$NSSF$	1,113,677	1.56	4.42
	high	light	$NSDF$	1,195,430	0.00	1.44
			$NSSF$	1,195,430	-2.72	10.61
	high	dark	$NSDF$	631,717	-0.01	1.29
			$NSSF$	631,717	2.07	8.74
SAC-C	low	dark	F	32,726	-1.62	3.19
	mid	dark	F	229,702	0.47	2.93
	high	dark	F	128,067	0.91	4.36
	low	light	$NSDF$	25,811	-0.02	0.67
			$NSSF$	25,811	4.60	9.53
	low	dark	$NSDF$	25,357	-0.01	0.52
			$NSSF$	25,357	-3.10	6.46
	mid	light	$NSDF$	181,785	0.00	1.27
			$NSSF$	181,785	1.00	6.98
	mid	dark	$NSDF$	187,818	-0.01	1.13
			$NSSF$	187,818	1.04	5.87
	high	light	$NSDF$	187,259	0.01	1.58
			$NSSF$	187,259	-3.05	11.88
	high	dark	$NSDF$	102,679	-0.05	1.32
			$NSSF$	102,679	1.81	8.75

The weighted residual statistics to the CM6 model are given in Table 1. The satellite scalar residuals are denoted as F and the vector residuals are in the frame where B is in the direction of the predicted field $\mathbf{B}$, P is in the direction of $\mathbf{n} \times \mathbf{B}$, where $\mathbf{n}$ is the common bore-sight direction, and 3 is in the direction of $(\mathbf{n} \times \mathbf{B}) \times \mathbf{B}$. The OHM residuals are in the NED frame, that is, $(North, East, Down)$. The satellite vector sums and differences are in the $BP3$ frame for CHAMP and the NED frame for Swarm and are prefixed with "NSS" and "NSD" for north-south sums and north-south differences, respectively. In the case of Swarm *Alpha* and *Charlie* east-west sums and differences, the notation "EWS" and "EWD" is used, respectively. In addition, "CHAMP 2ST" denotes residuals to measurements when two Star Trackers were available, and "CHAMP AST" and "CHAMP BST" denote residuals to measurements when only one of two types of single Star Tracker was available.

(13) **Please give some indication of the (co-)variances of the resulting set of coefficients.**

Table 2. CM6 weighted residual statistics for CHAMP 2ST

Name	Lat.	Sun	Comp.	N	Mean	RMS
CHAMP 2ST	low	light	$NSDB$	70,870	0.00	0.69
			$NSDP$	70,870	0.00	2.33
			$NSD3$	70,870	0.01	3.76
			$NSDF$	387,501	0.01	0.70
			$NSSB$	70,870	0.60	6.13
			$NSSP$	70,870	-0.35	7.71
			$NSS3$	70,870	-0.22	13.15
			SSF	387,501	2.61	6.72
	low	dark	B	218,425	-0.41	1.43
			P	218,425	0.07	1.87
			3	218,425	-0.07	1.98
			F	232, 657	-0.38	1.36
			$NSDB$	299,393	-0.00	0.189
			$NSDP$	299,393	-0.00	0.96
			$NSD3$	299,393	-0.00	1.34
			$NSDF$	312,300	0.00	0.18
			$NSSB$	299,393	-0.36	3.23
			$NSSP$	299,393	0.14	2.98
			$NSS3$	299,393	0.16	4.43
			$NSSF$	312,300	-0.90	2.87
	mid	light	$NSDB$	627,787	0.00	0.35
			$NSDP$	627,787	0.00	1.89
			$NSD3$	627,787	-0.00	3.54
			$NSDF$	1,921,194	-0.00	0.35
			$NSSB$	627,787	0.02	4.93
			$NSSP$	627,787	-0.15	6.91
			$NSS3$	627,787	-0.37	11.7
			$NSSF$	1,921,194	-0.11	5.05
	mid	dark	B	994,263	-0.12	1.20
			P	994,263	0.01	2.18
			3	994,263	0.01	2.36
			F	1,051,816	-0.12	1.15
			$NSDB$	1,362,408	-0.00	0.18
			$NSDP$	1,362,408	0.00	1.08
			$NSD3$	1,362,408	0.00	1.71
			$NSDF$	1,420,915	-0.00	0.17
			$NSSB$	1,362,408	-0.10	2.73
			$NSSP$	1,362,408	0.04	3.66
			$NSS3$	1,362,408	-0.11	5.70
			$NSSF$	1,420,915	-0.09	2.51
	high	light	$NSDF$	1,611,109	-0.00	1.14
			$NSSF$	1,611,109	-3.51	12.29
	high	dark	F	649,628	-0.62	4.76
			$NSDF$	853,816	0.00	1.03
			$NSSF$	853,816	-0.86	9.32

TABLE 3. CM6 weighted residual statistics for CHAMP AST

Name	Lat.	Sun	Comp.	N	Mean	RMS
CHAMP AST	low	light	$NSDB$	135,842	-0.01	0.81
			$NSDP$	135,842	0.00	2.67
			$NSD3$	135,842	0.03	1.99
			$NSSB$	135,842	2.53	7.01
			$NSSP$	135,842	-0.21	13.88
			$NSS3$	135,842	-1.66	14.75
	low	dark	B	10,904	-0.31	1.59
			P	10,904	-0.85	4.47
			3	10,904	0.60	4.96
			$NSDB$	4,718	-0.00	0.26
			$NSDP$	4,718	0.20	3.97
			$NSD3$	4,718	0.08	1.92
			$NSSB$	4,718	-0.72	3.36
			$NSSP$	4,718	-0.27	8.32
			$NSS3$	4,718	-0.10	6.50
	mid	light	$NSDB$	562,152	-0.06	0.40
			$NSDP$	562,152	-0.00	2.39
			$NSD3$	562,152	0.04	2.26
			$NSSB$	562,152	-0.04	5.32
			$NSSP$	562,152	-0.10	11.13
			$NSS3$	562,152	0.07	12.60
	mid	dark	B	41,103	-0.30	1.39
			P	41,103	-0.59	6.00
			3	41,103	0.16	5.02
			$NSDB$	19,292	-0.00	0.22
			$NSDP$	19,292	0.06	3.62
			$NSD3$	19,292	0.01	4.22
			$NSSB$	19,292	-0.08	2.96
			$NSSP$	19,292	-0.09	8.36
			$NSS3$	19,292	-0.59	9.75

These were extracted from the calibrated, formal error-covariance matrix and are listed in the tables of submitted coefficients. The calibration factor, s^2, on the formal error-covariance matrix is estimated by

$$s^2 = \frac{\mathbf{r}^{\mathrm{T}}\mathbf{W}\mathbf{r}}{N - M}, \tag{4}$$

where $\mathbf{r}$ is the *a posteriori* residual vector, $\mathbf{W}$ is the measurement noise covariance matrix, N is the number of measurements, and M is the number of model coefficients. For CM6 we have $s^2 = 1.9$. Therefore, the uncertainties listed in the candidate coefficient tables are extracted from the calibrated error-covariance matrix that now correctly reflects the actual observed residuals to the model. As mentioned earlier, the uncertainties for IGRF2020 are taken from the linearly propagated calibrated error-covariance matrix.

Table 4. CM6 weighted residual statistics for CHAMP BST

Name	Lat.	Sun	Comp.	N	Mean	RMS
CHAMP BST	low	light	$NSDB$	171,352	0.00	0.79
			$NSDP$	171,352	-0.02	2.79
			$NSD3$	171,352	-0.03	2.00
			$NSSB$	171,352	2.54	6.78
			$NSSP$	171,352	-0.11	13.80
			$NSS3$	171,352	-1.27	14.52
	low	dark	B	10,904	-0.31	1.59
			P	10,904	-0.85	4.47
			3	10,904	0.60	4.96
			$NSDB$	10,234	-0.02	0.27
			$NSDP$	10,234	-0.04	3.17
			$NSD3$	10,234	0.02	1.91
			$NSSB$	10,234	-0.73	3.38
			$NSSP$	10,234	-0.45	7.92
			$NSS3$	10,234	-1.74	7.87
	mid	light	$NSDB$	702,924	0.06	0.40
			$NSDP$	702,924	0.01	2.56
			$NSD3$	702,924	-0.04	2.49
			$NSSB$	702,924	-0.26	5.26
			$NSSP$	702,924	-0.77	11.49
			$NSS3$	702,924	0.19	13.18
	mid	dark	B	41,103	-0.30	1.39
			P	41,103	-0.59	5.99
			3	41,103	0.12	5.03
			$NSDB$	36,237	-0.00	0.23
			$NSDP$	36,237	0.02	3.17
			$NSD3$	36,237	0.05	3.76
			$NSSB$	36,237	-0.04	2.83
			$NSSP$	36,237	-0.21	8.17
			$NSS3$	36,237	-1.10	10.28

Table 5. CM6 weighted residual statistics for Swarm *Alpha*

Name	Lat.	Sun	Comp.	N	Mean	RMS
Swarm *Alpha*	low	light	$NSDN$	221,433	0.00	0.61
			$NSDE$	221,433	0.00	0.78
			$NSDD$	221,433	-0.00	0.77
			$NSDF$	221,823	0.01	0.53
			$NSSN$	221,433	2.11	6.72
			$NSSE$	221,433	-0.17	12.08
			$NSSD$	221,433	0.19	6.90
			$NSSF$	221,823	2.04	6.28
	low	dark	B	174,238	-0.75	1.89
			P	174,238	0.13	1.81
			3	174,238	0.01	1.58
			F	174,626	-0.73	1.87
			$NSDN$	174,223	-0.00	0.18
			$NSDE$	174,223	0.00	0.32
			$NSDD$	174,223	-0.01	0.31
			$NSDF$	174,622	0.00	0.15
			$NSSN$	174,223	-1.33	3.26
			$NSSE$	174,223	0.18	3.02
			$NSSD$	174,223	-0.01	2.59
			$NSSF$	174,622	-1.15	3.08
	mid	light	$NSDN$	1,080,692	-0.00	0.53
			$NSDE$	1,080,692	-0.00	0.82
			$NSDD$	1,080,692	0.00	0.48
			$NSDF$	1,083,813	-0.00	0.30
			$NSSN$	1,080,692	0.01	6.91
			$NSSE$	1,080,692	0.16	8.88
			$NSSD$	1,080,692	0.01	5.03
			$NSSF$	1,083,813	0.11	4.65
	mid	dark	B	782794	0.03	1.50
			P	782794	-0.03	2.53
			3	782794	0.05	2.48
			F	784,514	0.04	1.49
			$NSDN$	782,748	0.00	0.23
			$NSDE$	782,748	0.00	0.35
			$NSDD$	782,748	0.00	0.24
			$NSDF$	784,498	0.00	0.16
			$NSSN$	782,748	-0.75	3.98
			$NSSE$	782,748	0.02	4.08
			$NSSD$	782,748	0.05	2.72
			$NSSF$	784,498	0.08	2.50
	high	light	$NSDF$	908,670	0.01	0.97
			$NSSF$	908,670	-2.86	10.85
	high	dark	F	479,693	0.01	5.13
			$NSDF$	479,005	0.01	0.89
			$NSSF$	479,005	0.01	8.15

Table 6. CM6 weighted residual statistics for Swarm *Bravo*

Name	Lat.	Sun	Comp.	N	Mean	RMS
Swarm *Bravo*	low	light	$NSDN$	218,538	-0.00	0.54
			$NSDE$	218,538	0.01	0.72
			$NSDD$	218,538	0.01	0.70
			$NSDF$	220,198	0.00	0.46
			$NSSN$	218,538	2.23	7.61
			$NSSE$	218,538	-0.32	12.51
			$NSSD$	218,538	0.05	6.70
			$NSSF$	220,198	2.11	7.06
	low	dark	B	173,570	-0.88	2.96
			P	173,570	0.155	2.32
			3	173,570	-0.09	1.86
			F	174,393	-0.90	2.98
			$NSDN$	173,564	-0.00	0.17
			$NSDE$	173,564	-0.00	0.30
			$NSDD$	173,564	0.00	0.30
			$NSDF$	174,390	0.00	0.16
			$NSSN$	173,564	-1.35	4.98
			$NSSE$	173,564	0.19	3.79
			$NSSD$	173,564	-0.16	2.80
			$NSSF$	174,390	-1.31	4.83
	mid	light	$NSDN$	1,065,714	-0.00	0.52
			$NSDE$	1,065,714	0.00	0.80
			$NSDD$	1,065,714	0.00	0.47
			$NSDF$	1,073,230	0.00	0.28
			$NSSN$	1,065,714	0.00	7.78
			$NSSE$	1,065,714	0.02	9.46
			$NSSD$	1,065,714	-0.03	5.29
			$NSSF$	1,073,230	0.05	5.15
	mid	dark	B	781,225	0.06	2.16
			P	781,225	0.02	2.83
			3	781,225	0.09	3.23
			F	785,113	0.07	2.15
			$NSDN$	781,198	0.01	0.28
			$NSDE$	781,198	-0.00	0.34
			$NSDD$	781,198	-0.00	0.23
			$NSDF$	785,111	-0.00	0.17
			$NSSN$	781,198	-0.74	5.52
			$NSSE$	781,198	0.12	4.58
			$NSSD$	781,198	0.03	3.22
			$NSSF$	785,111	0.14	3.52
	high	light	$NSDF$	912,630	0.01	0.87
			$NSSF$	912,630	-2.80	10.41
	high	dark	F	475,222	0.23	4.94
			$NSDF$	474,772	-0.00	0.79
			$NSSF$	474,772	0.32	7.93

Table 7. CM6 weighted residual statistics for Swarm *Charlie*

Name	Lat.	Sun	Comp.	N	Mean	RMS
Swarm *Charlie*	low	light	$NSDN$	221,512	0.00	0.61
			$NSDE$	221,512	0.00	0.78
			$NSDD$	221,512	-0.00	0.77
			$NSDF$	221,900	0.00	0.53
			$NSSN$	221,512	2.08	6.65
			$NSSE$	221,512	-0.23	11.85
			$NSSD$	221,512	-0.00	6.88
			$NSSF$	221,900	2.00	6.23
	low	dark	B	174,320	-0.65	1.83
			P	174,320	0.04	1.80
			3	174,320	-0.17	1.59
			F	174,619	-0.67	1.83
			$NSDN$	174,310	-0.00	0.18
			$NSDE$	174,310	0.00	0.32
			$NSDD$	174,310	0.00	0.31
			$NSDF$	174,611	-0.01	0.15
			$NSSN$	174,310	-1.17	3.14
			$NSSE$	174,310	0.0.4	3.01
			$NSSD$	174,310	-0.31	2.61
			$NSSF$	174,611	-1.06	3.02
	mid	light	$NSDN$	1,080,624	-0.00	0.54
			$NSDE$	1,080,624	-0.00	0.82
			$NSDD$	1,080,624	-0.00	0.48
			$NSDF$	1,084,481	-0.00	0.30
			$NSSN$	1,080,624	0.00	6.90
			$NSSE$	1,080,624	0.00	8.90
			$NSSD$	1,080,624	0.03	5.03
			$NSSF$	1,084,481	0.12	4.61
	mid	dark	B	783,941	0.11	1.50
			P	783,941	-0.10	2.53
			3	783,941	0.03	2.46
			F	785,422	0.10	1.50
			$NSDN$	783,894	0.00	0.29
			$NSDE$	783,894	0.00	0.35
			$NSDD$	783,894	-0.00	0.24
			$NSDF$	785,411	0.00	0.16
			$NSSN$	783,894	-0.59	3.95
			$NSSE$	783,894	-0.11	4.08
			$NSSD$	783,894	0.06	2.72
			$NSSF$	785,411	0.21	2.51
	high	light	$NSDF$	909,406	0.01	0.97
			$NSSF$	909,406	-2.71	10.74
	high	dark	F	480,103	0.13	5.12
			$NSDF$	479,401	0.01	0.89
			$NSSF$	479,401	0.20	8.15

Table 8. CM6 weighted residual statistics for Swarm *Alpha* and *Charlie*

Name	Lat.	Sun	Comp.	N	Mean	RMS
Swarm *Alpha* & *Charlie*	low	light	$EWDN$	202,668	-0.03	0.61
			$EWDE$	202,668	0.00	1.79
			$EWDD$	202,668	-0.07	1.21
			$EWDF$	203,238	-0.01	0.49
			$EWSN$	202,668	2.21	6.69
			$EWSE$	202,668	-0.20	11.72
			$EWSD$	202,668	-0.02	6.74
			$EWSF$	203,238	2.15	6.26
	low	dark	$EWDN$	158,737	0.10	0.40
			$EWDE$	158,737	-0.00	0.79
			$EWDD$	158,737	-0.11	0.55
			$EWDF$	159,297	0.07	0.35
			$EWSN$	158,737	-1.32	3.21
			$EWSE$	1587,37	0.15	2.84
			$EWSD$	158,737	-0.24	2.52
			$EWSF$	159,297	-1.154	3.06
	mid	light	$EWDN$	987,491	-0.02	0.75
			$EWDE$	987,491	0.00	1.49
			$EWDD$	987,491	0.02	0.70
			$EWDF$	991,990	0.01	0.44
			$EWSN$	987,491	0.04	6.86
			$EWSE$	987,491	0.13	8.71
			$EWSD$	987,491	0.00	4.96
			$EWSF$	991,990	9 0.18	4.62
	mid	dark	$EWDN$	714,780	0.10	0.45
			$EWDE$	714,780	-0.00	0.80
			$EWDD$	714,780	0.03	0.38
			$EWDF$	717, 285	0.07	0.32
			$EWSN$	714,780	-0.71	3.97
			$EWSE$	714,780	-0.05	4.02
			$EWSD$	714,780	0.06	2.7
			$EWSF$	717,285	0.14	2.51
	high	light	$EWDF$	823,477	0.10	0.57
			$EWSF$	823,477	-2.85	10.96
	high	dark	$EWDF$	446,674	0.10	0.54
			$EWSF$	446,674	0.14	8.32

Table 9. CM6 weighted residual statistics for OHMs

Name	Lat.	Sun	Comp.	N	Mean	RMS
OHM	low	light	N	269,547	1.22	12.31
			E	269,547	-0.07	8.92
			D	269,547	-0.13	8.73
	low	dark	N	210,378	-0.10	7.40
			E	210,378	-0.97	4.86
			D	210,378	0.69	4.75
	mid	light	N	3,656,755	-0.27	6.24
			E	3,656,755	-0.38	6.51
			D	3,656,755	-0.18	5.20
	mid	dark	N	2,519,210	0.00	3.98
			E	2,519,210	0.01	4.20
			D	2,519,210	-0.02	3.62
	high	light	N	1,448,143	1.68	14.17
			E	1,448,143	-1.05	11.57
			D	1,448,143	-0.63	13.82
	high	dark	N	718,401	0.07	10.59
			E	718,401	-0.08	8.49
			D	718,401	0.02	11.13