Swarm Expert Support Laboratories

Proposal for Update of VFM - STR Euler Angles

British Geological Survey (BGS)
National Space Institute – DTU Space (DTU)
Delft Institute of Earth Observation and Space Systems (DUT)
Helmholtz Centre Potsdam - German Research Centre for Geosciences (GFZ)
Eidgenössische Technische Hochschule Zürich (ETH)
Institut de Physique du Globe de Paris (IPGP)
The Swedish Institute of Space Physics (IRF)
Laboratoire d'électronique des technologies de l'information (Leti)
University of Calgary (UoC)
Aerospace Research And Test Establishment (VZLU)

with additional contributions from

NASA Goddard Space Flight Center (GSFC)
University of Colorado (CIRES)
Charles University Prague (CUP)

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Record of Changes

Reason	Description	Rev	Date
Initial release	Initial version of document.	1dA	2014-06-30

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1 Introduction

1.1 Scope and applicability

This document is a constituent of the Design Definition file and is provided in response to an Action Item from the Swarm Quality Working Group meeting in Copenhagen 2014-06-18 to provide an updated set of transformations from the VFM vector magnetometer sensor frame to the STR Star Tracker common reference frame for all three Swarm spacecrafts. Within the scientific community these transformations are often described by sets of Euler angles and are often simply referred to as "*The Euler Angles of Swarm*".

2 Applicable and Reference Documentation

2.1 Applicable Documents

The following documents are applicable to the definitions within this document.

[AD-1] RFQ/3-13759/12/I-NB, Request For Quotation

[AD-2] SWAM-GSEG-EOPG-SW-12-0059, ESL Statement of Work (Appendix 1 of [AD-1])

2.2 Reference Documents

None.

2.3 Abbreviations

Acronym ***or abbreviation***	***Description***
APDF	Archiving and Payload Data Facility
Aux	Auxiliary
BGS	British Geological Survey, GB
CCDB	Characterisation and Calibration DataBase
CCN	Contract Change Notice
CIRES	Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, US
CUP	Charles University Prague, CZ
DTU	Technical University of Denmark, DK
DUT	Delft University of Technology, NL
EFI	Electrical Field Instrument, including the TII and the LP
ESA	European Space Agency

Acronym ***or abbreviation***	***Description***
ESL	Swarm Expert Support Laboratories
ESRIN	European Space Research Institute, Frascati, IT
ETH	Eidgenössische Technische Hochschule Zürich, CH
GFZ	Helmholtz Centre Potsdam - German Research Centre for Geoscience, DE
GSFC	NASA Goddard Space Flight Center, US
IGRF	International Geomagnetic Reference Field
IOC	In Orbit Commissioning
IOCR	In Orbit Commissioning Review
IPGP	Institut de Physique du Globe de Paris, FR
JIRA	Atlassian JIRA internet based tool for tracking issues with server located at DTU https://jira.spacecenter.dk/
L0	Level 0 (satellite data)
L1	Level 1 (satellite data)
L1b	Level 1b (satellite data)
MPPF	Mission Planning and Performance Facility
NEC	Nort-East-Center reference frame
PDGS	Payload Data Ground Segment
PP	Prototype Processor
QWG	Quality Working Group
SCARF	Satellite Constellation Application and Research Facility. Same as L2PS.
STR	Star Tracker
SVN	SVN Repository with server located at DTU. Presently, the following URLs apply: https://smart-svn.spacecenter.dk/svn/smart/SwarmESL-All https://smart-svn.spacecenter.dk/svn/smart/SwarmL2 (heritage from the L2PS Project)
Swarm	Constellation of 3 ESA satellites, http://www.esa.int/esaLP/ESA3QZJE43D_LPswarm_0.html
TBC	To Be Confirmed
TBD	To Be Defined

Acronym *or abbreviation*	*Description*
TDS	Test Data Set
UoC	University of Calgary (CA)
VFM	Vector Field Magnetometer
VZLU	Výzkumný a zkušební letecký ústav, or Aerospace Research And Test Establishment (CZ)

3 CCDB Update Summary

The proposed updates of the Swarm CCDB auxiliary files are given in the following tables. The justification of the updates is given in Section 4.

Table 3-1 Swarm A CCDB Update

Filename	SW_OPER_AUXASW1_C__20000101T000000_99999999T999999_0007.EEF
Complete XPATH or Columns/rows index	TBD
File line	239-242
Tag affected	Structure.STR_q_VFM
Field Format	Quaternion
Old value	<Q1>-0.013315150439779</Q1> <Q2>0.618889028865068</Q2> <Q3>0.022648803785932</Q3> <Q4>0.785038921586876</Q4>
New value	<Q1>-0.013231661342904</Q1> <Q2>0.618887980270184</Q2> <Q3>0.022658176820283</Q3> <Q4>0.785040889405373</Q4>
Start validity	20000101T000000
Stop validity	99999999T999999
TDS package name	SW-TN-DTU-GS-004_TDS-1: ftp://ftp.space.dtu.dk/data/magnetic-satellites/Swarm/SCARF/Test/L1b_Euler_Test.zip ftp://ftp.space.dtu.dk/data/magnetic-satellites/Swarm/SCARF/Test/L1b_Euler_Test2.zip
Note	Ref. SW-TN-DTU-GS-004

Table 3-2 Swarm B CCDB Update

Filename	SW_OPER_AUXBSW1_C__20000101T000000_99999999T999999_0007.EEF
Complete XPATH or Columns/rows	TBD

index	
File line	239-242
Tag affected	Structure.STR_q_VFM
Field Format	Quaternion
Old value	<Q1>0.011647432672848</Q1> <Q2>0.619604649109814</Q2> <Q3>-0.014720424875213</Q3> <Q4>0.784689572509491</Q4>
New value	<Q1> 0.011665364843673</Q1> <Q2>0.619618032648957</Q2> <Q3>-0.014476629065635</Q3> <Q4>0.784683273741830</Q4>
Start validity	20000101T000000
Stop validity	99999999T999999
TDS package name	SW-TN-DTU-GS-004_TDS-1: ftp://ftp.space.dtu.dk/data/magnetic-satellites/Swarm/SCARF/Test/L1b_Euler_Test.zip ftp://ftp.space.dtu.dk/data/magnetic-satellites/Swarm/SCARF/Test/L1b_Euler_Test2.zip
Note	Ref. SW-TN-DTU-GS-004

Table 3-3 Swarm C CCDB Update

Filename	SW_OPER_AUXCSW1_C__20000101T000000_99999999T999999_0007.EEF
Complete XPATH or Columns/rows index	TBD
File line	239-242
Tag affected	Structure.STR_q_VFM
Field Format	Quaternion
Old value	<Q1>-0.001663135699780</Q1> <Q2>0.621398648445704</Q2> <Q3>0.003605958231516</Q3> <Q4>0.783484492989318</Q4>
New value	<Q1>-0.001666461237559</Q1> <Q2>0.621375398504043</Q2>

	<Q3>0.003700375477998</Q3> <Q4>0.783502485166580</Q4>
Start validity	20000101T000000
Stop validity	99999999T999999
TDS package name	SW-TN-DTU-GS-004_TDS-1: ftp://ftp.space.dtu.dk/data/magnetic-satellites/Swarm/SCARF/Test/L1b_Euler_Test.zip ftp://ftp.space.dtu.dk/data/magnetic-satellites/Swarm/SCARF/Test/L1b_Euler_Test2.zip
Note	Ref. SW-TN-DTU-GS-004

4 Description of Swarm Euler Angle Update

The update of the "Swarm Euler Angles", i.e. of the transformation from the VFM vector magnetometer sensor frame to the STR Star Tracker Common Reference Frame (CRF), is aimed at improving the accuracy of the Swarm vector magnetic data provided in the North-East-Center (NEC) frame, i.e. of the B_NEC elements of the Level 1b low-rate magnetic products, MAG*X*_LR_1B. These products are expected to be widely used by the geomagnetic science community for the upcoming International Geomagnetic Reference Field model (IGRF) epoch 2015.

4.1 Derivation

The updated VFM → STR transformations are obtained through advanced modelling of Earth's magnetic field performed by GFZ and DTU independently using Swarm MAG*X*_LR_1B products version 0301covering the period from launch (2013-11-22) until end of May 2014. The modelling of GFZ also includes a model of the observed discrepancies between the Absolute Scalar Magnetometer (ASM) and VFM readings. Note that this model of the ASM-VFM discrepancies has not been incorporated in the TDS.

The estimated transformations and their deviations with respect to one-another and with respect to the values in CCDB version 0007 (cf. Section 3) are given in Table 4-1.

Table 4-1 Estimated Transformations and Differences

S/C	GFZ	DTU	Deviation, arc-sec.		
			GFZ-DTU	GFZ- CCDB	DTU- CCDB
A	-0.013269375978100 0.618902374293704 0.022669990762100 0.785028563985805	-0.013231661342904 0.618887980270184 0.022658176820283 0.785040889405373	18.1	21.9	34.7
B	0.011677752680200 0.619629627018087 -0.014419179131600 0.784674991755783	0.011665364843673 0.619618032648957 -0.014476629065635 0.784683273741830	24.9	125.5	101.0
C	-0.001685485468600 0.621383811058280 0.003731711833400 0.783495623995575	-0.001666461237559 0.621375398504043 0.003700375477998 0.783502485166580	15.8	53.2	40.8

4.2 Justification

The estimated transformations listed in Table 4-1 have been applied to Swarm MAG*X*_LR_1B products version 0301covering the months December 2013 and May 2014 to form the Test Data Set (TDS). The TDS has been analysed by Arnaud Chulliat and Patrick Alken of NOAA and the reports on their findings are enclosed in Annex A. Based on their results and in agreement with GFZ (cf. Annex B), the transformations estimated by DTU are proposed implemented within PDGS.

Annex A TDS Analyses

On the following pages, the analyses by NOAA of the TDS are provided.

Analysis of Swarm datasets prepared from revised Euler angles

Arnaud Chulliat, Univ. Colorado & NOAA/NGDC
2014-06-27

Method:
For each dataset (DTU and GFZnew), MF models were calculated from one month of data and one satellite. Hence a total of 12 models were calculated. Preprocessing of the data included standard data selection for quiet-time and nighttime data; vector data below +/-55 degrees geomagnetic latitude and scalar data at higher latitudes. Crustal (MF7 model) and external (POMME7) models were removed from the data prior to the inversion. MF was calculated until degree 20 and damped with minimum energy norm at the core.

Results:
See Tables 1-2 and Figures 1-3 below.

1. The overall situation is much improved by using the new datasets. There are many more green cells than yellow and red cells in Table 2.
2. The DTU dataset consistently improves the situation for all satellites and epochs. The biggest deterioration for this dataset (in May 2014, satellite B, mean dB_r residuals) is less than 0.5 nT (Table 2). The average slopes in the residuals vs. colatitude graphs for the Y component are much reduced with respect to the baseline dataset, although not entirely horizontal (Figs. 1-3).
3. The GFZnew dataset consistently improves the situation for satellites A and C, all epochs, although with slightly more yellow cells than the DTU dataset (Table 2). This is also seen in the residuals vs. colatitude graphs in which the average slopes are larger than for the DTU dataset (Figs. 1 and 3).
4. There seems to be a problem with the GFZnew dataset for satellite B, December 2013, as the mean dB_r and dB_phi residuals are deteriorated with respect to the baseline dataset (Table 2). This is also prominent in the residuals vs. colatitude graph (Fig. 2). Interestingly, the mean dB_phi residuals for the DTU dataset are smaller but the difference between December and May (-1.96-1.84=-3.80) is comparable with that for the GFZ dataset (-3.87+0.11=-3.76). This could suggest that the time variation of the Euler angles for that satellite is not negligible.

Satellite A

Dec 2013	0301 baseline		DTU angles		GFZnew angles	
	mean	rms	mean	rms	mean	rms
dB_r	0.53	2.14	0.31	2.07	1.02	2.33
dB_theta	0.37	3.61	0.37	3.65	0.35	3.60
dB_phi	1.33	4.73	-0.93	2.92	-0.41	3.62

May 2014	0301 baseline		DTU angles		GFZnew angles	
	mean	rms	mean	rms	mean	rms
dB_r	-0.24	2.31	-0.19	2.24	-0.76	2.36
dB_theta	0.30	4.67	0.34	4.56	0.34	4.60
dB_phi	2.98	4.51	0.74	2.66	1.27	2.94

Satellite B

Dec 2013	0301 baseline		DTU angles		GFZnew angles	
	mean	rms	mean	rms	mean	rms
dB_r	0.05	3.38	0.51	3.11	1.05	3.22
dB_theta	0.39	4.70	0.42	4.40	0.40	4.39
dB_phi	3.23	6.45	-1.96	3.37	-3.87	5.02

May 2014	0301 baseline		DTU angles		GFZnew angles	
	mean	rms	mean	rms	mean	rms
dB_r	-0.15	2.29	-0.61	2.20	-1.09	2.39
dB_theta	0.48	4.23	0.24	4.52	0.29	4.48
dB_phi	2.73	6.40	1.84	3.19	-0.11	2.27

Satellite C

Dec 2013	0301 baseline		DTU angles		GFZnew angles	
	mean	rms	mean	rms	mean	rms
dB_r	1.04	2.67	0.21	2.51	0.61	2.54
dB_theta	0.32	3.86	0.32	3.94	0.31	3.93
dB_phi	1.97	4.17	-0.65	2.78	-1.13	3.57

May 2014	0301 baseline		DTU angles		GFZnew angles	
	mean	rms	mean	rms	mean	rms
dB_r	-0.89	2.49	0.11	2.20	-0.18	2.17
dB_theta	0.32	4.61	0.32	4.52	0.35	4.55
dB_phi	3.29	5.92	0.61	2.68	0.15	2.46

mean < 1	rms < 4
1 < mean < 2	4 < rms < 5
mean > 2	rms > 5

Table 1: Mean and rms residuals for each model, with cells colored so as to highlight the largest mean and rms values.

Satellite A

Dec 2013	0301 baseline		DTU angles		GFZnew angles	
	mean	rms	mean	rms	mean	rms
dB_r	0.53	2.14	0.31	2.07	1.02	2.33
dB_theta	0.37	3.61	0.37	3.65	0.35	3.60
dB_phi	1.33	4.73	-0.93	2.92	-0.41	3.62

May 2014	0301 baseline		DTU angles		GFZnew angles	
	mean	rms	mean	rms	mean	rms
dB_r	-0.24	2.31	-0.19	2.24	-0.76	2.36
dB_theta	0.30	4.67	0.34	4.56	0.34	4.60
dB_phi	2.98	4.51	0.74	2.66	1.27	2.94

Satellite B

Dec 2013	0301 baseline		DTU angles		GFZnew angles	
	mean	rms	mean	rms	mean	rms
dB_r	0.05	3.38	0.51	3.11	1.05	3.22
dB_theta	0.39	4.70	0.42	4.40	0.40	4.39
dB_phi	3.23	6.45	-1.96	3.37	-3.87	5.02

May 2014	0301 baseline		DTU angles		GFZnew angles	
	mean	rms	mean	rms	mean	rms
dB_r	-0.15	2.29	-0.61	2.20	-1.09	2.39
dB_theta	0.48	4.23	0.24	4.52	0.29	4.48
dB_phi	2.73	6.40	1.84	3.19	-0.11	2.27

Satellite C

Dec 2013	0301 baseline		DTU angles		GFZnew angles	
	mean	rms	mean	rms	mean	rms
dB_r	1.04	2.67	0.21	2.51	0.61	2.54
dB_theta	0.32	3.86	0.32	3.94	0.31	3.93
dB_phi	1.97	4.17	-0.65	2.78	-1.13	3.57

May 2014	0301 baseline		DTU angles		GFZnew angles	
	mean	rms	mean	rms	mean	rms
dB_r	-0.89	2.49	0.11	2.20	-0.18	2.17
dB_theta	0.32	4.61	0.32	4.52	0.35	4.55
dB_phi	3.29	5.92	0.61	2.68	0.15	2.46

improvement
worsening < 1 nT
worsening > 1 nT

Table 2: Same as Table 1, but with cells colored so as to highlight when the new Euler angles lead to an improvement or a worsening of the mean and rms residuals.

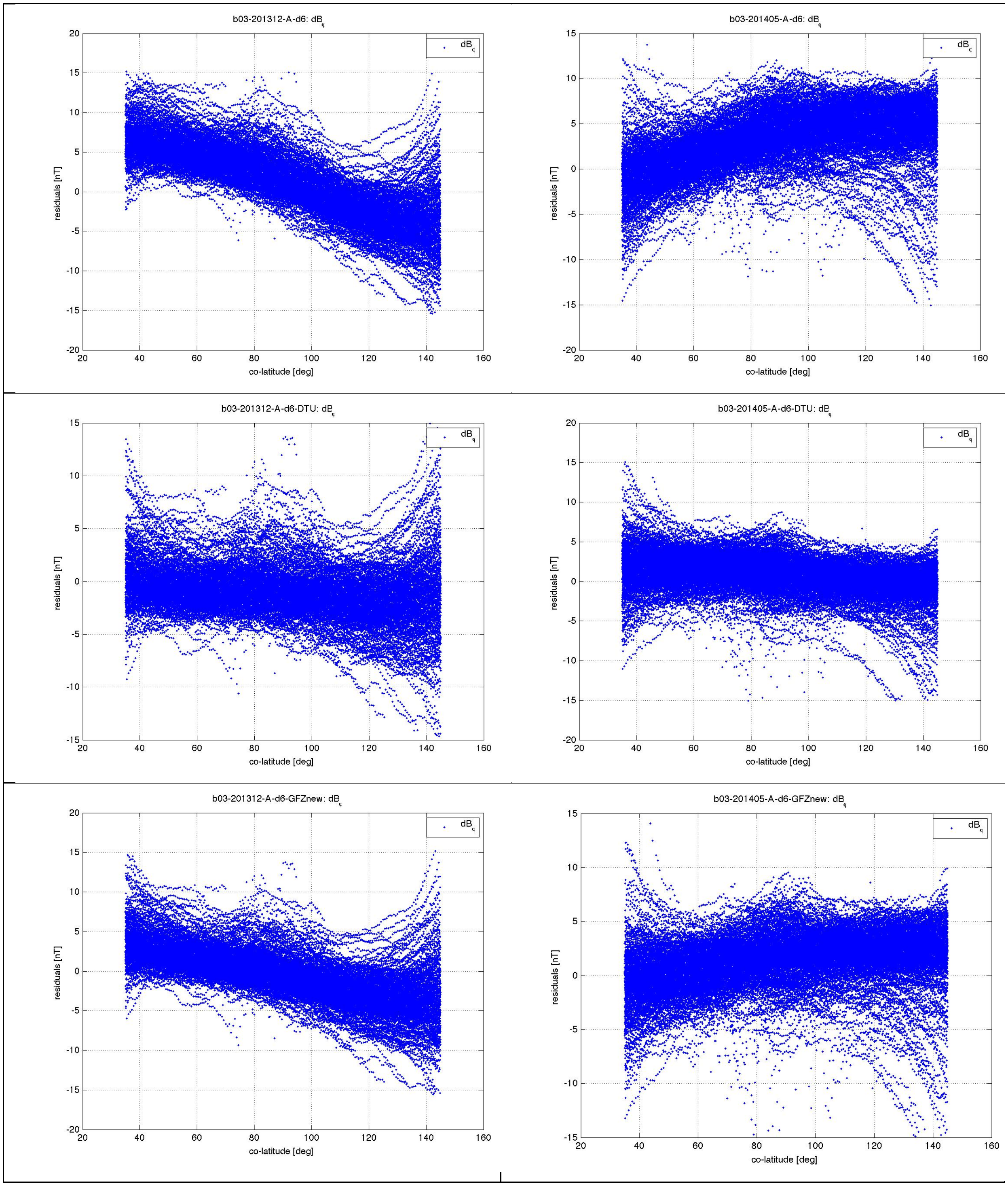


Figure 1: B_{φ} (Y) residuals, satellite A, for December 2013 (left) and May 2014 (right), and for baseline (top), DTU (middle) and GFZnew (bottom) datasets.

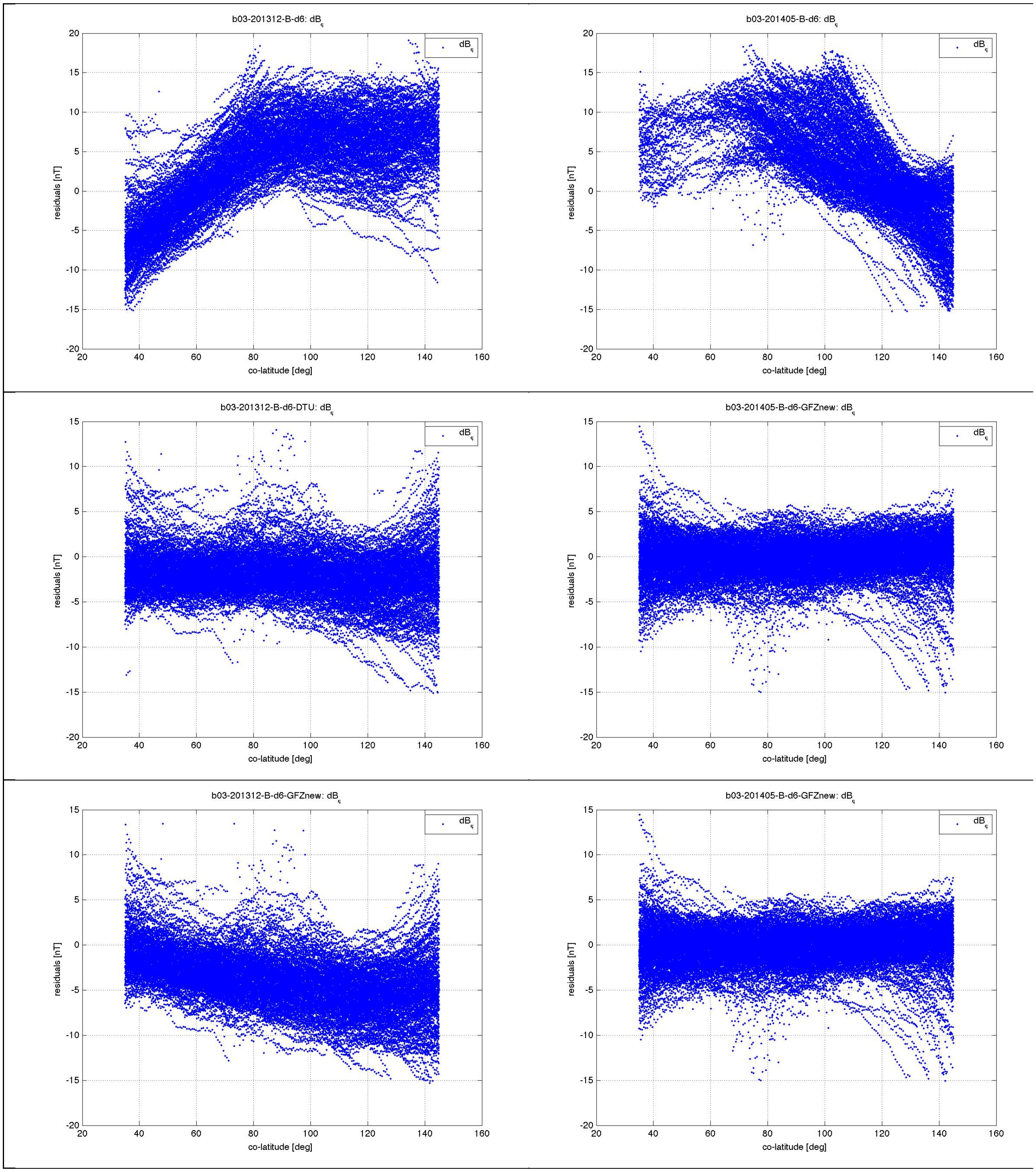


Figure 2: B_φ (Y) residuals, satellite B, for December 2013 (left) and May 2014 (right), and for baseline (top), DTU (middle) and GFZnew (bottom) datasets.

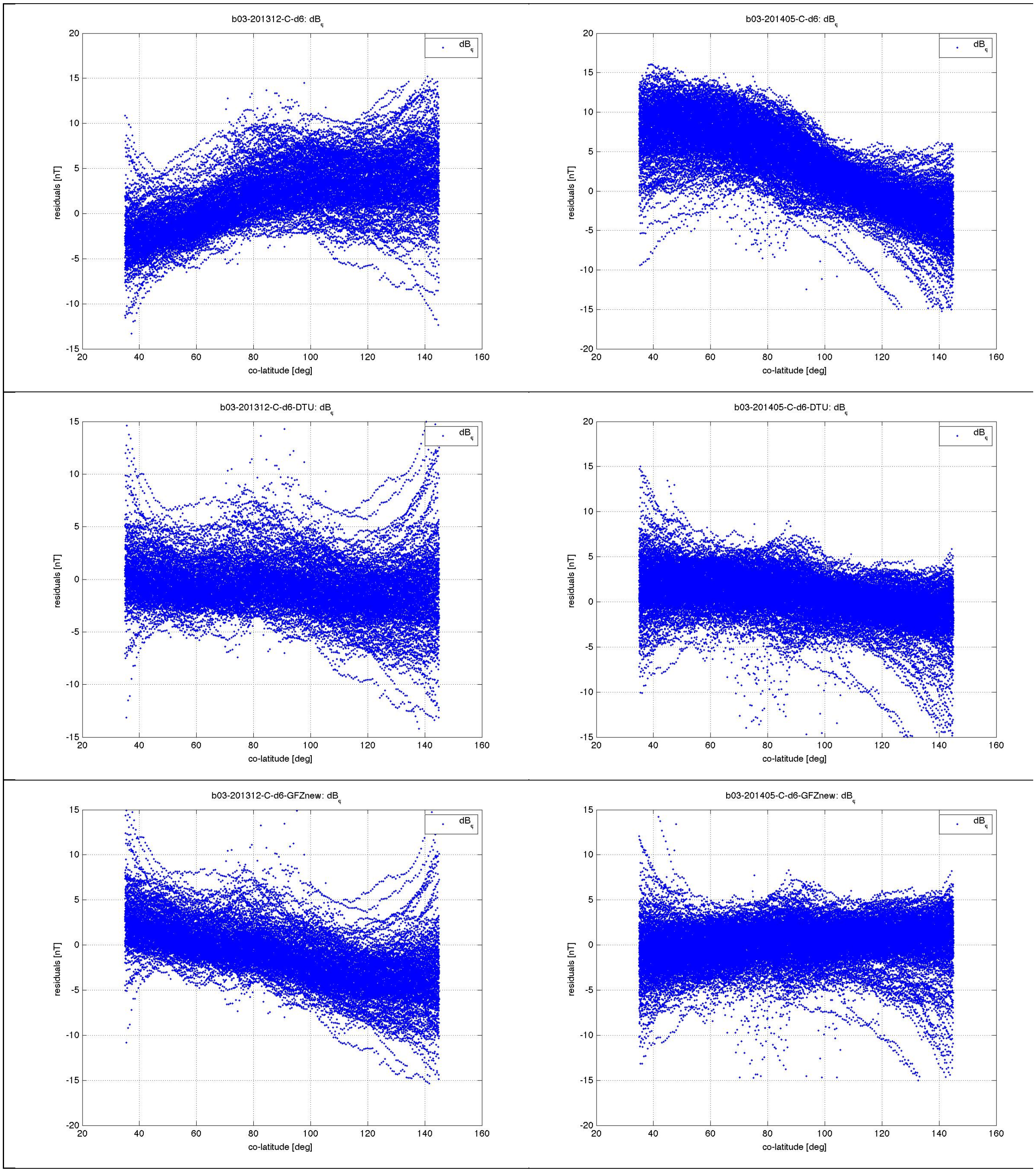


Figure 3: B_{φ} (Y) residuals, satellite C, for December 2013 (left) and May 2014 (right), and for baseline (top), DTU (middle) and GFZnew (bottom) datasets.

Summary

27 June 2014

Patrick Alken

NGDC/NOAA Boulder, CO, USA

To analyze the Euler angle results provided by DTU and GFZ, I've constructed main field models for Swarm A,B,C using the DTU and GFZ datasets. In both datasets, there is drastic improvement over the 0301 baseline in the X and Y NEC components.

The models were constructed to spherical harmonic degree 15, with secular variation to degree 8. The POMME-7 external field was subtracted from the data prior to fitting, and a simple daily ring current field aligned with the internal dipole was coestimated to account for errors in POMME.

I made 3 sets of models. The first uses data only in December 2013, the second uses data in May 2014, and the third combines the two datasets. In the tables below, I provide the rms values for the residuals in X, Y, Z (NEC frame). The color scheme is as follows. If a model based on one set of Euler angles has a lower rms than the same model built from the other set of Euler angles, it is shown in green. Otherwise, it is shown in red. Therefore, when comparing the DTU and GFZ results below, green indicates a better residual distribution.

Generally speaking, I don't find a large difference between the two (ie: sometimes the GFZ dataset gives a lower rms, and sometimes the DTU dataset has a lower rms). In many cases, the rms values between the two datasets are extremely close, though DTU does have (slightly) more green cells than GFZ in the tables below.

For the B satellite in December, both the DTU and GFZ angles give slightly larger rms values for each component, however the GFZ rms is significantly higher in the Y component.

Both datasets exhibit latitudinal dependence in the Y residuals (see the residual plots). I have plotted the residuals only for the DTU dataset, but the GFZ residuals look similar. In both cases, the Y residuals have a clear linear change with respect to latitude, while the X and Z are fairly flat.

My main conclusion is this:

Both DTU and GFZ angles are a huge improvement over the 0301 baseline. Both DTU and GFZ datasets exhibit a linear latitudinal dependence in Y whose origin is unknown. I am unable to state that either dataset is clearly superior to the other, though DTU has more green cells in the tables below indicating slightly lower rms residual values overall, but these rms differences are generally extremely small.

Residual rms

Swarm A

DTU

Component	December	May	Combined
X	3.76	4.68	4.26

Y	3.54	3.53	3.57
Z	2.25	2.87	2.54

GFZ (new angles)

Component	December	May	Combined
X	3.72	4.69	4.25
Y	4.27	3.56	3.99
Z	2.25	2.88	2.58

Swarm B

DTU

Component	December	May	Combined
X	5.44	4.67	5.12
Y	4.03	3.93	4.01
Z	3.96	2.73	3.41

GFZ (new angles)

Component	December	May	Combined
X	5.55	4.64	5.16
Y	5.61	3.28	4.62
Z	3.98	2.69	3.46

Swarm C

DTU

Component	December	May	Combined
X	4.59	4.55	4.64
Y	3.19	3.63	3.46
Z	3.33	2.82	3.08

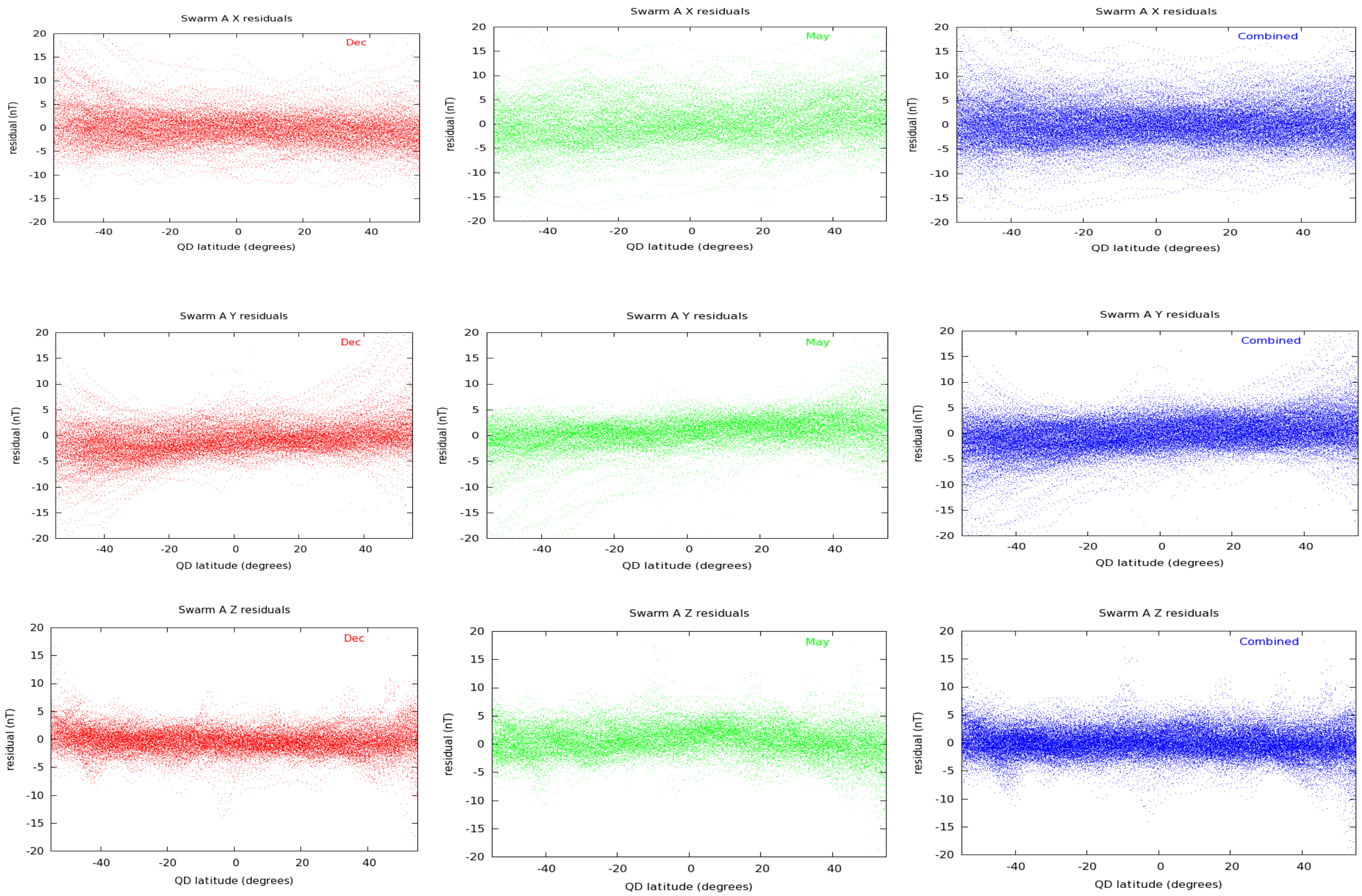
GFZ (new angles)

Component	December	May	Combined
X	4.62	4.56	4.65
Y	4.03	3.37	3.74
Z	3.31	2.79	3.08

Residual plots (DTU)

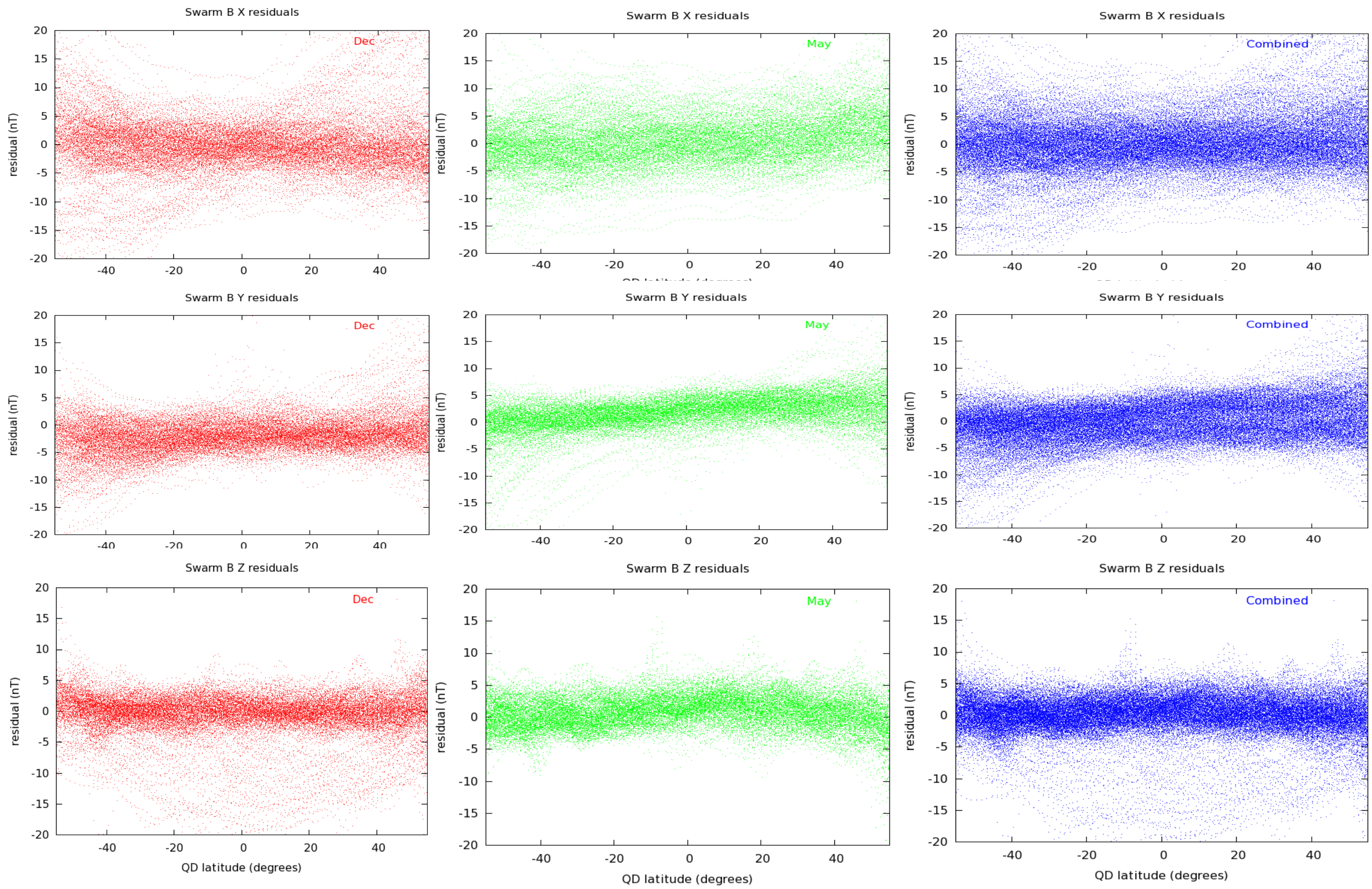
Swarm A

December May Combined



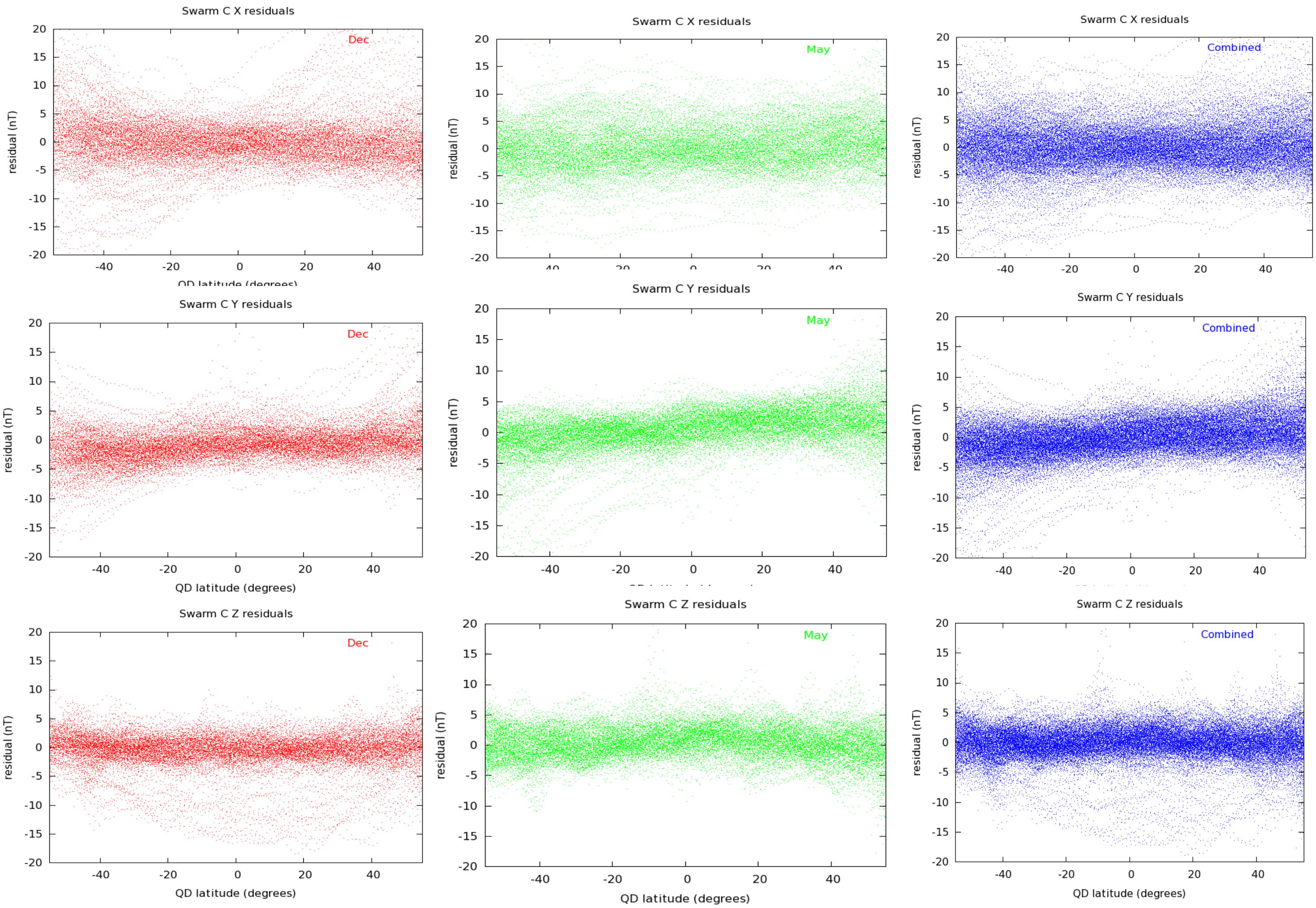
Swarm B

December May Combined



Swarm C

December | May | Combined



Annex B Answer from Vincent Lesur, GFZ

Subject: Re: delays in Euler angles processing
From: Vincent Lesur <lesur@gfz-potsdam.de>
Date: 30-06-2014 09:26
To: Arnaud Chulliat - NOAA Affiliate <arnaud.chulliat@noaa.gov>
CC: Lars Tøffner-Clausen <lastec@space.dtu.dk>, Nils Olsen <nio@space.dtu.dk>, Chris Finlay <cfinlay@space.dtu.dk>, Patrick Alken <patrick.alken@noaa.gov>, "Martin K.A. Rother" <rother@gfz-potsdam.de>, Gauthier Hulot <gh@ipgp.fr>

Dear All,

I looked at Arnaud and Patrick's comments and I think it is very encouraging that the analysis gives similar results. The Euler angle values we sent were based on a data set that has been corrected for a perturbation vector estimated from the ASM/VFM scalar differences. It is therefore not a surprise if the Euler angles we provided are not optimum when used with an un-corrected data set. However, we have not been able to test if our perturbation vector estimates are valid. This is a work to be done with IPGP. In view of the results, and aware of possible difficulties with our perturbation vector estimates, I would recommend that we use DTU Euler angles data sets to process the next version of Swarm data.

Best regards

Vincent

On 28 Jun 2014, at 02:00, Arnaud Chulliat - NOAA Affiliate <arnaud.chulliat@noaa.gov> wrote:

> Dear Lars,
>
> Attached are the results of two independent analysis by Patrick and myself of the new "DTU" and "GFZnew" datasets. We note a very significant improvement of the residuals when using either dataset, but there are differences between the two datasets. Overall, the DTU angles give slightly better results, especially for satellite B. Please let us know if you would like us to do other calculations and/or provide other information about our results.
>
> Best regards and have a great week-end!
>
> Arnaud
>
> On Fri, Jun 27, 2014 at 5:26 AM, Lars Tøffner-Clausen <lastec@space.dtu.dk> wrote:
>
>> Dear Arnaud
>>
>> I have now received the new Euler angles from GFZ and uploaded new data to ftp://ftp.space.dtu.dk/data/magnetic-satellites/Swarm/SCARF/Test/L1b_Euler_Test2.zip.
>>
>> Below, I have listed some numbers (as in my previous mail). Please note: GFZ has corrected the vector measurements using Vincent's model of the stray field. This correction has not