Met Office

8th EUMETSAT ROM SAF user workshop on GNSS radio occultation measurements

1D Var Ionospheric Electron Density Retrieval – Analysis and Problematic Cases

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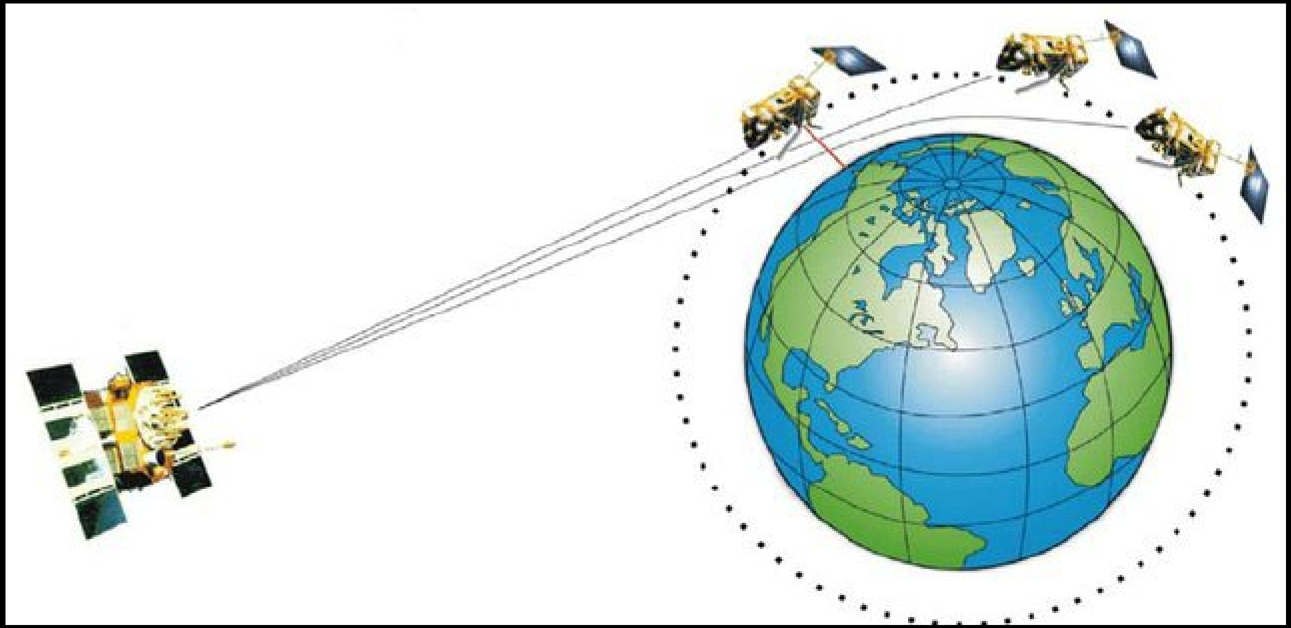
Outline

- Introduction
  - 1D Var for Ionospheric Electron Density Retrieval
  - Current experiment and QC
- Analysis of RO profiles using 2 and 3 layers
  - Plots of good and bad retrievals
  - Comparison of metadata statistics
- Validation with ionosonde measurements
- Summary and Future work



Picture credits: Hans Gleisner

1D Var for Ionospheric Electron Density Retrieval

- Under ROMSAF, the ROPP code has been developed as 1D ionospheric ED retrieval systems for Metop-SG to retrieve the parameters for a multi-layer Vary-Chap model.
- Involves adjusting a state vector, x, to minimise the cost function:

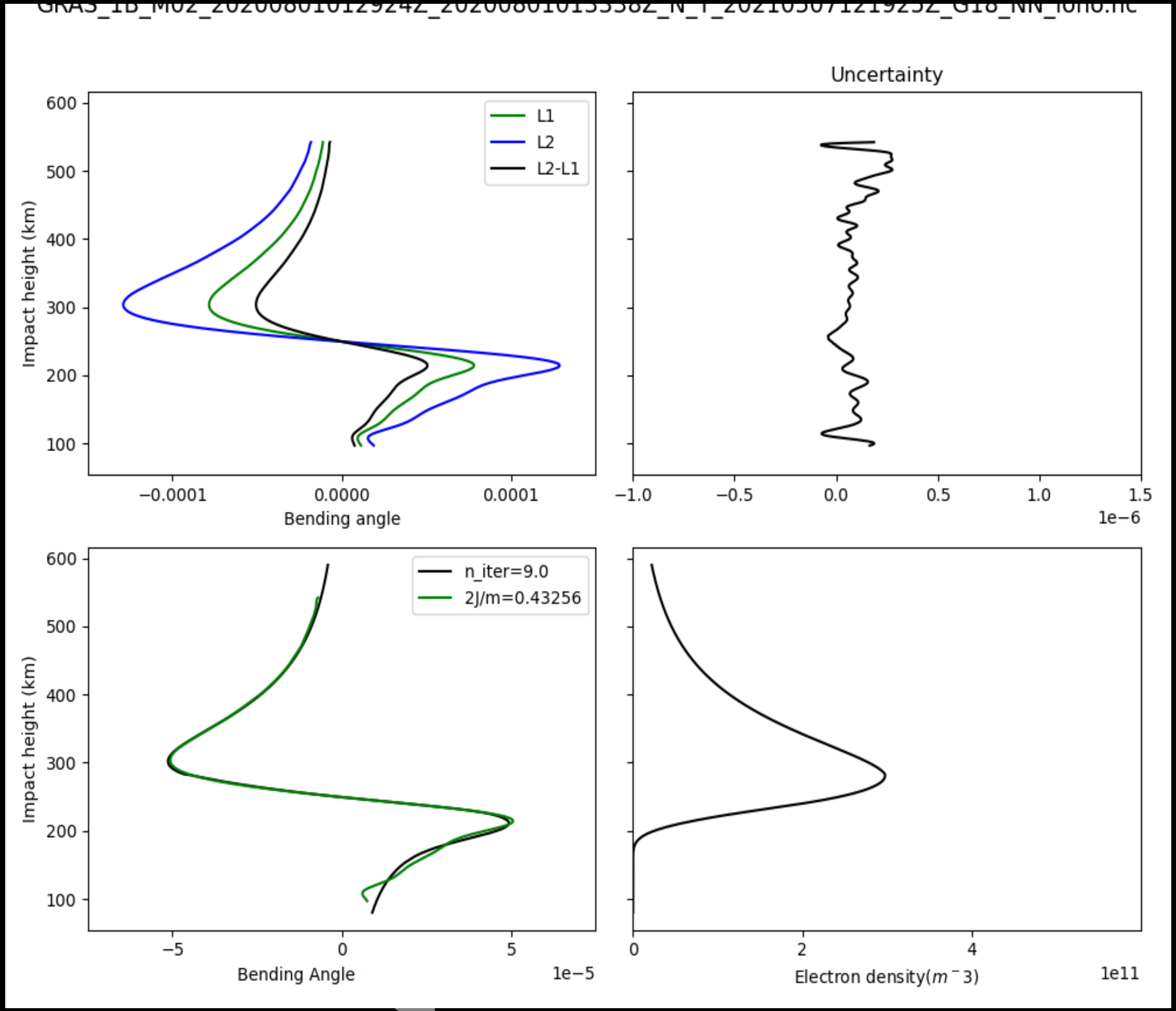
$$J(\mathbf{x}) = \frac{1}{2}(\mathbf{x}-\mathbf{x}_b)^{\mathbf{T}}\mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}_b) + \frac{1}{2}(\mathbf{y}-H(\mathbf{x}))^{\mathbf{T}}\mathbf{R}^{-1}(\mathbf{y}-H(\mathbf{x}))$$

where,

- xb is the a priori estimate of the state
- y is the vector of observations – Bending angles
- H is the forward operator, mapping parameters in x to the observation space and
- B and R are the a priori and observation error covariance matrices, respectively.

- **Purpose**: The goal of the 1D-Var method is to find the state *x* that minimizes the cost function *J(x)* and compute the $(\alpha_2 - \alpha_1)$ using the forward operator by adjusting the parameters to the best fit.

What does a good retrieval mean?



- Ionospheric density profile for 01/08/2020 - recreated from Healy (2023) using the ROPP code and MetOp data

- α_1 = Bending Angle at f1 (1575.42 MHz)
- α_2 = Bending Angle at f2 (1227.60 MHz)

- Consistency check (Bending Angle uncertainty estimate) using:

$$\alpha_2 - \left(\frac{f_1}{f_2}\right)^2 \alpha_1$$

- 2J/m = scaled cost function
- n_iter = number of iterations required

Current experiments and QC criterion

- **Observation Data:** Covering RO profiles from 16/07/2020 - 26/08/2020 with about 550 occ/day – total of ~24k profiles

- 1. Baseline: ROPP 11 for 2 layers: Active region – 150-500 km

- 2. Updated: ROPP 11 for 2 layers: Active region – 150-500 km, accounting for:
  - Missing data > 900 µrad
  - Large uncertainty errors >10 µrad

- 3. Updated ROPP 11 for 3 layers: Active region – 100-500 km

- Current QC based on *n_iter, 2J/m, consistency check*

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ANALYSIS OF RO PROFILES USING METOP EXTENSION DATA

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Performance Analysis of ROPP-11 Improved 2 layer/3 layer

2 layers

	time	lat	lon	n_iter	J_scaled
count	23990	23990.000000	23990.000000	23990.000000	23990.000000
mean	2009-04-01 00:03:34.552620544	-0.648416	-0.098468	12.120800	5.163855
min	2009-04-01 00:03:34.552620	-89.587852	-179.994827	3.000000	0.000000
25%	2009-04-01 00:03:34.552620032	-42.543309	-91.330755	9.000000	0.171305
50%	2009-04-01 00:03:34.552620032	-1.954315	-1.812766	11.000000	0.612260
75%	2009-04-01 00:03:34.552620032	41.710363	91.282291	14.000000	2.538811
max	2009-04-01 00:03:34.552620	89.700485	179.998032	50.000000	1604.221069
std	NaN	47.703881	104.653964	5.594209	27.611596

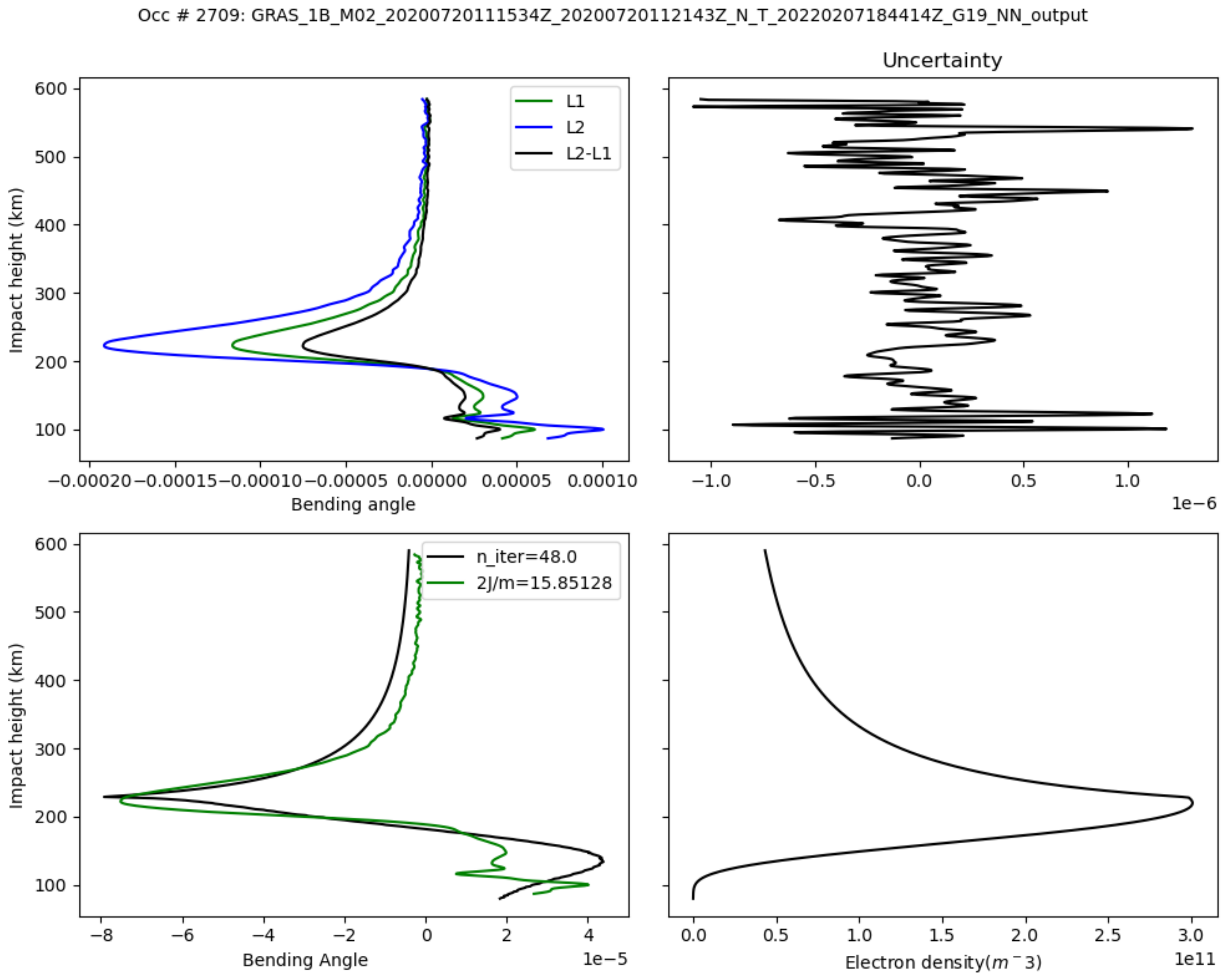
3 layers

	filedate_occultation_start	lat	lon	n_iter	J_scaled
count	23983	23983.000000	23983.000000	23983.000000	23983.000000
mean	2020-08-05 12:20:09.789058816	-0.660669	-0.122742	14.052370	4.646886
min	2020-07-16 00:00:42	-89.587900	-179.995000	3.000000	0.000000
25%	2020-07-25 22:31:11.500000	-42.553150	-91.340000	10.000000	0.374524
50%	2020-08-05 02:12:20	-1.997680	-1.833800	13.000000	1.044980
75%	2020-08-16 12:14:26	41.705250	91.223200	17.000000	2.817690
max	2020-08-26 23:33:14	89.700500	179.998000	50.000000	2103.040000
std	NaN	47.702923	104.642535	6.233055	23.116940

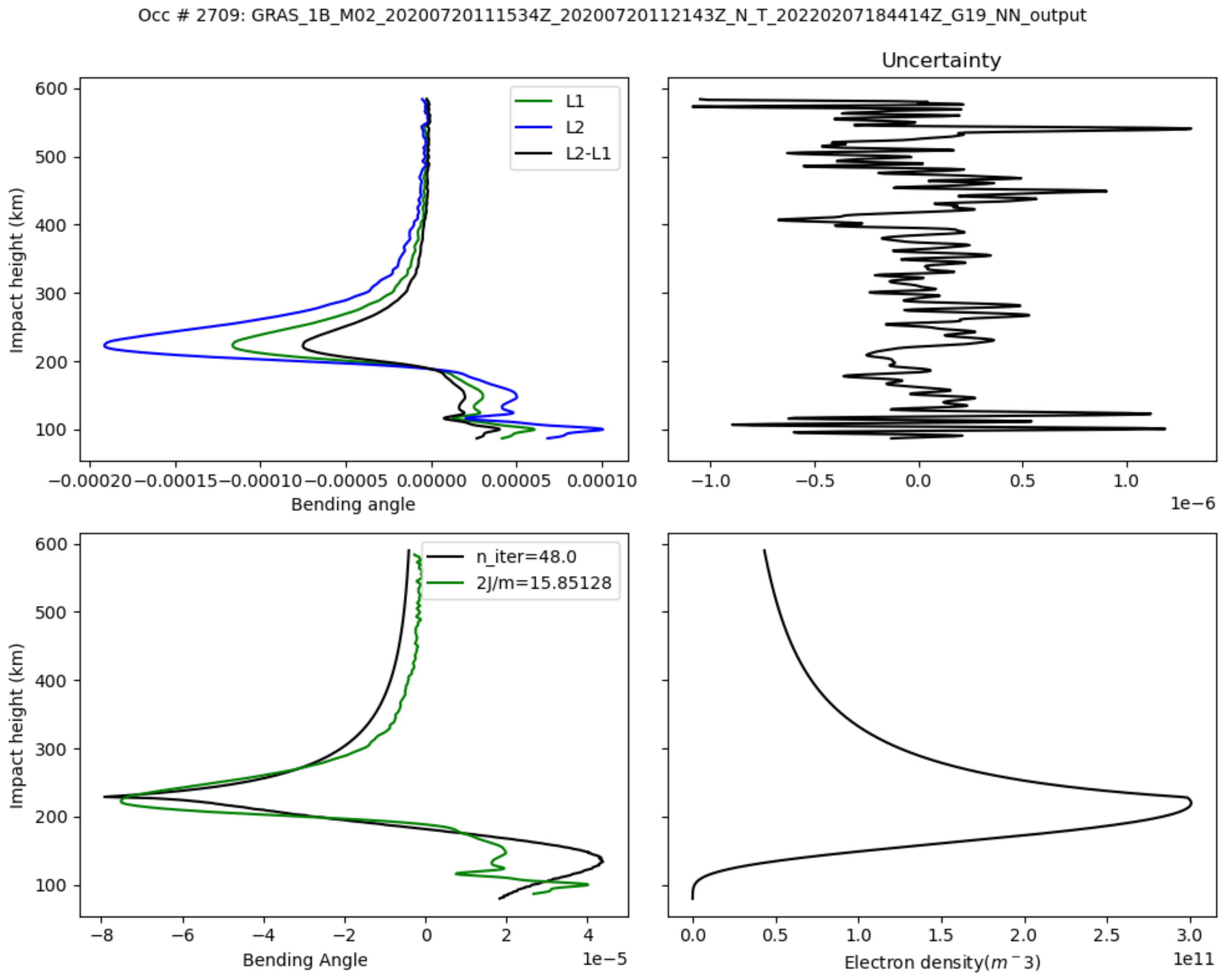
Improvement in the 2J/m mean value from ROPP 11 baseline is almost 91% and that from new baseline is 10.01% which is significant.

Case 1: ROPP 11 baseline vs improved

2 layer_ROPP 11 baseline

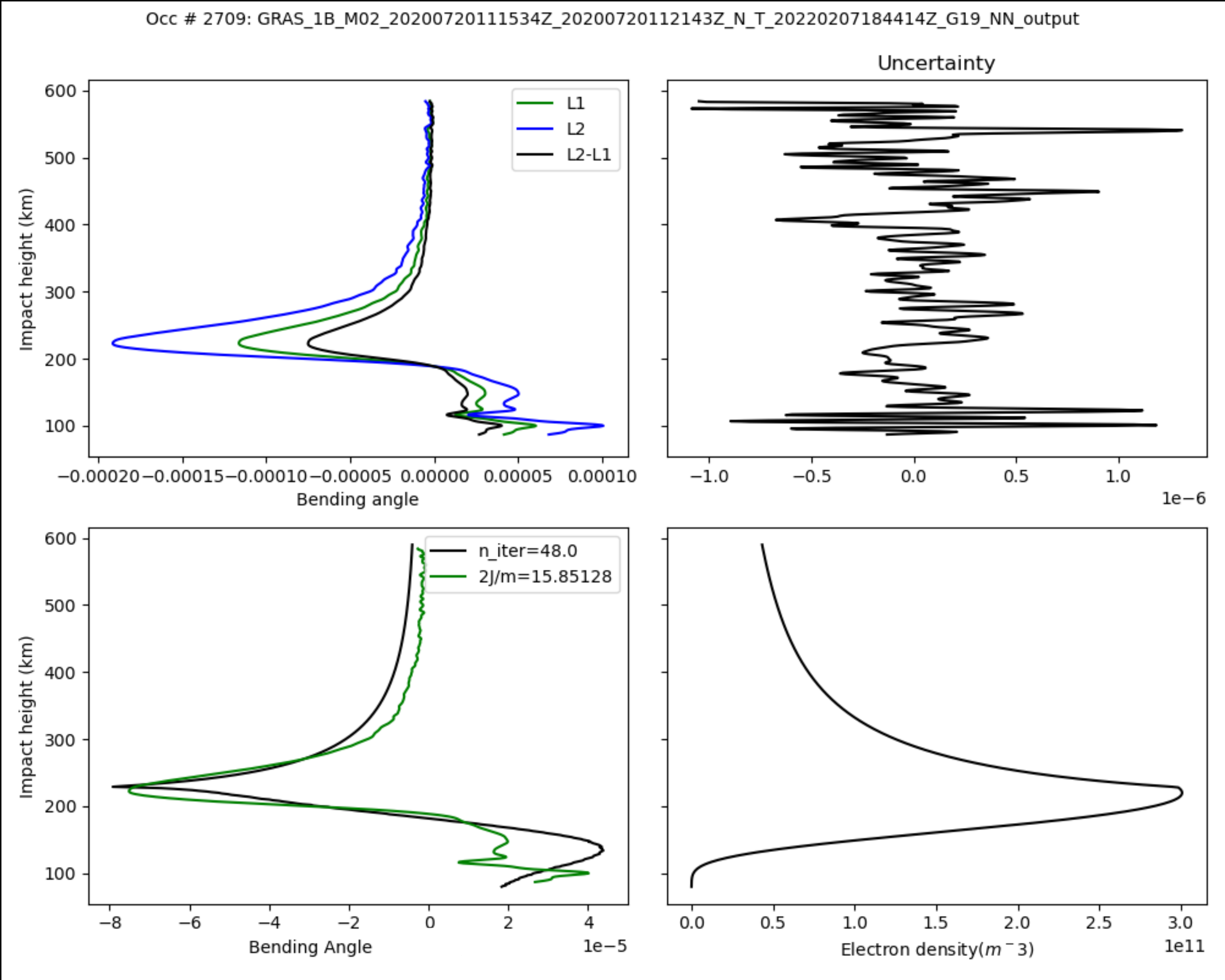


2 layer_improved

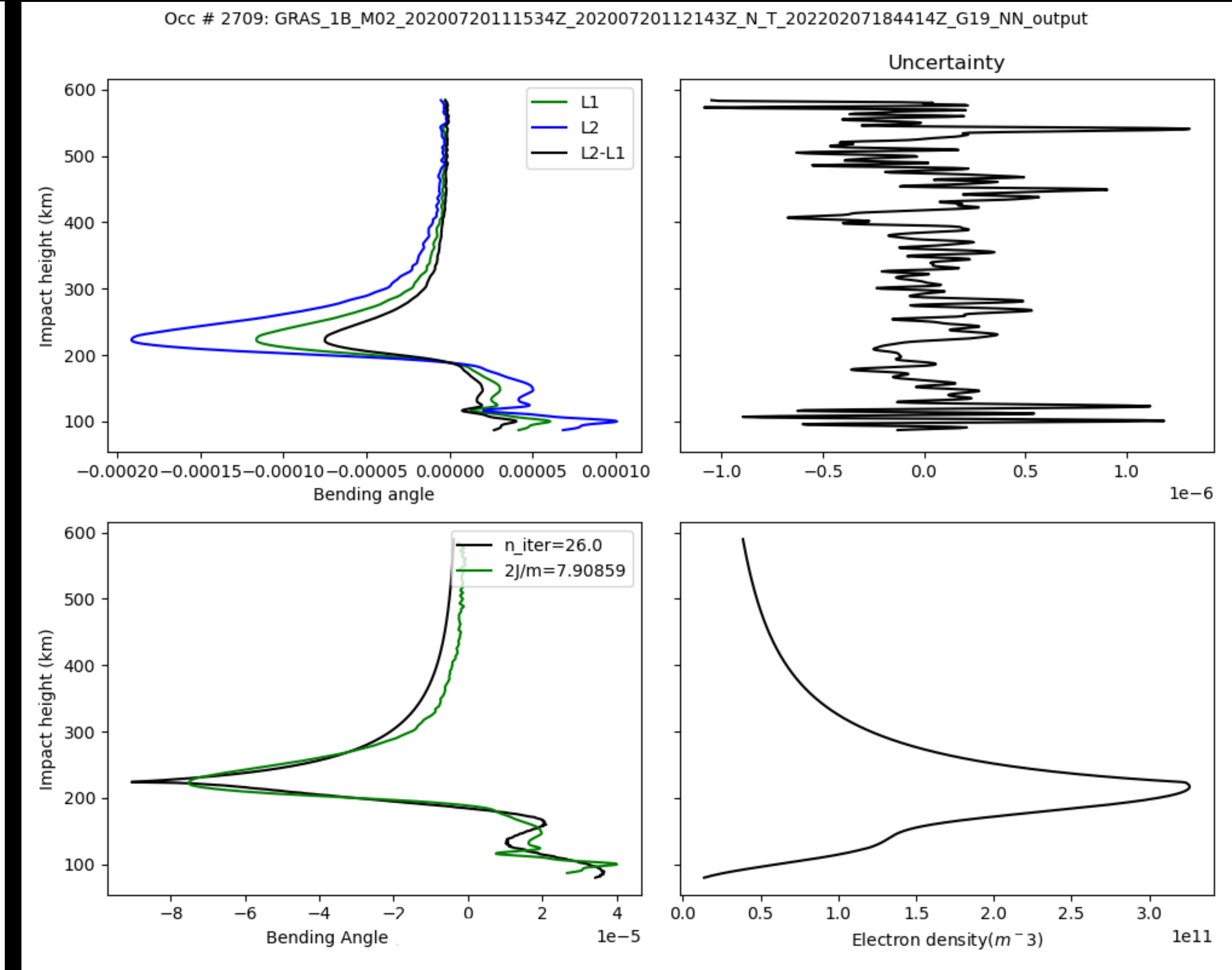


Case I: Improved metadata with 3rd layer

2 layer_improved

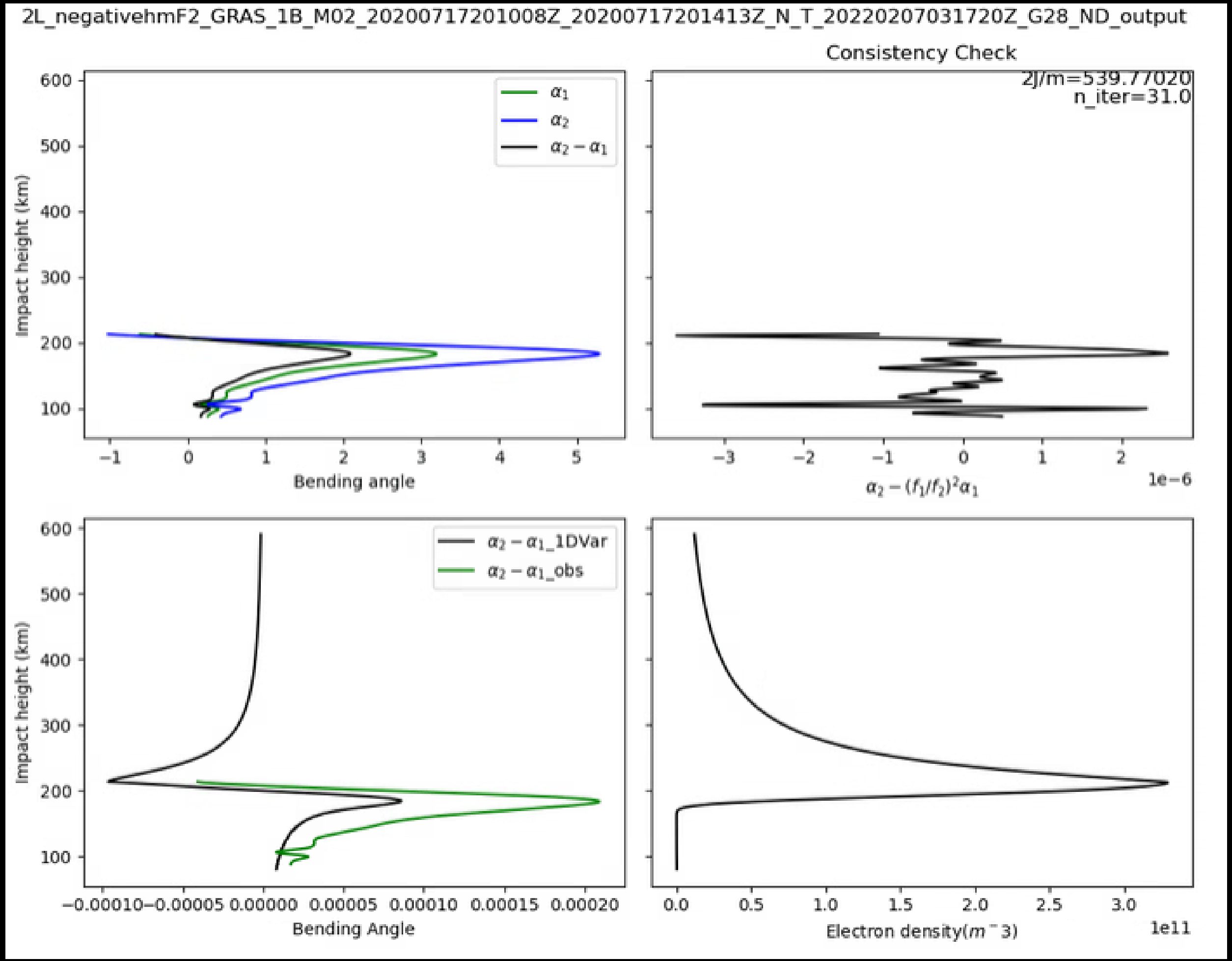


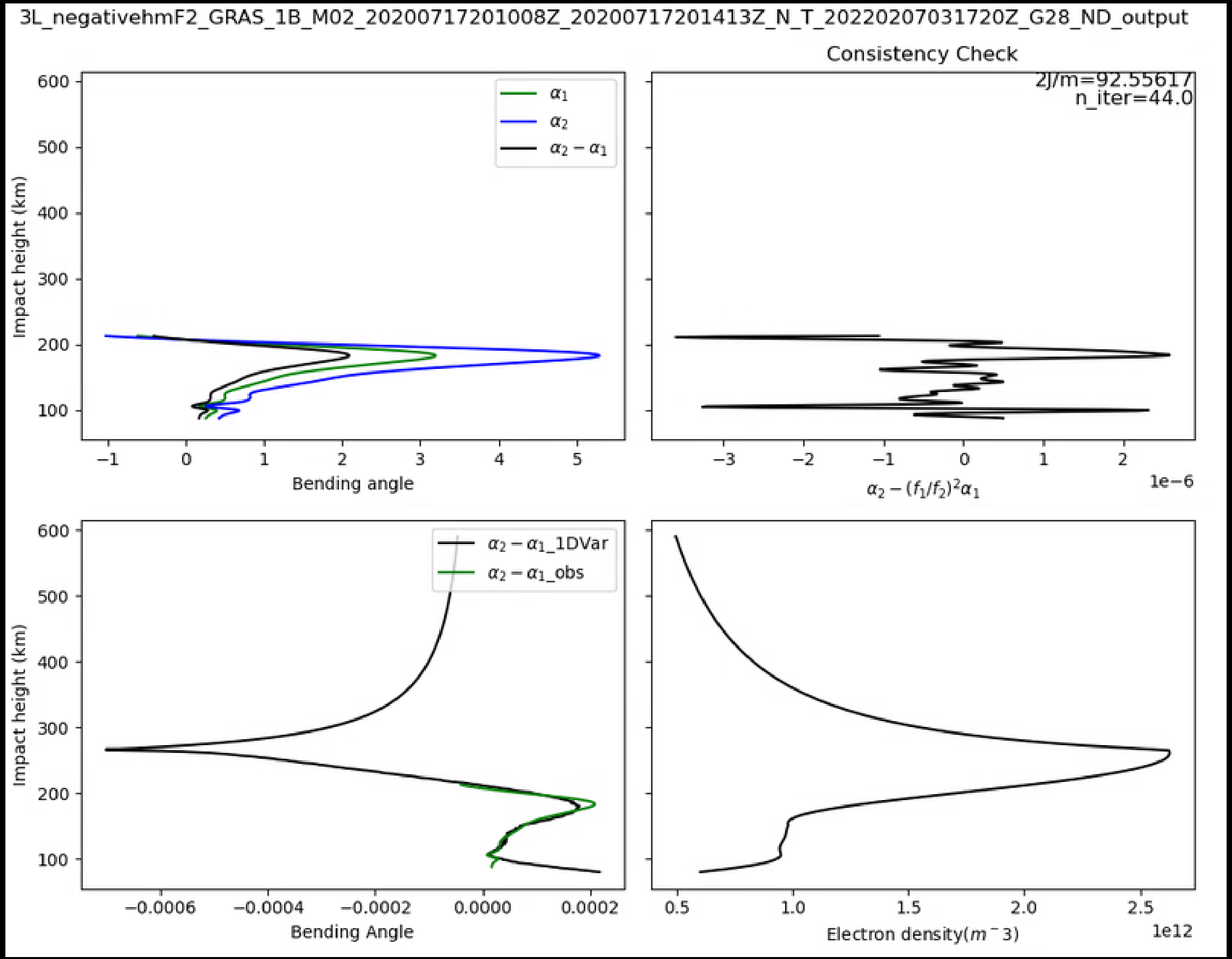
3 layer_improved



Case II: Negative hmF2

62 profiles with negative hmF2!

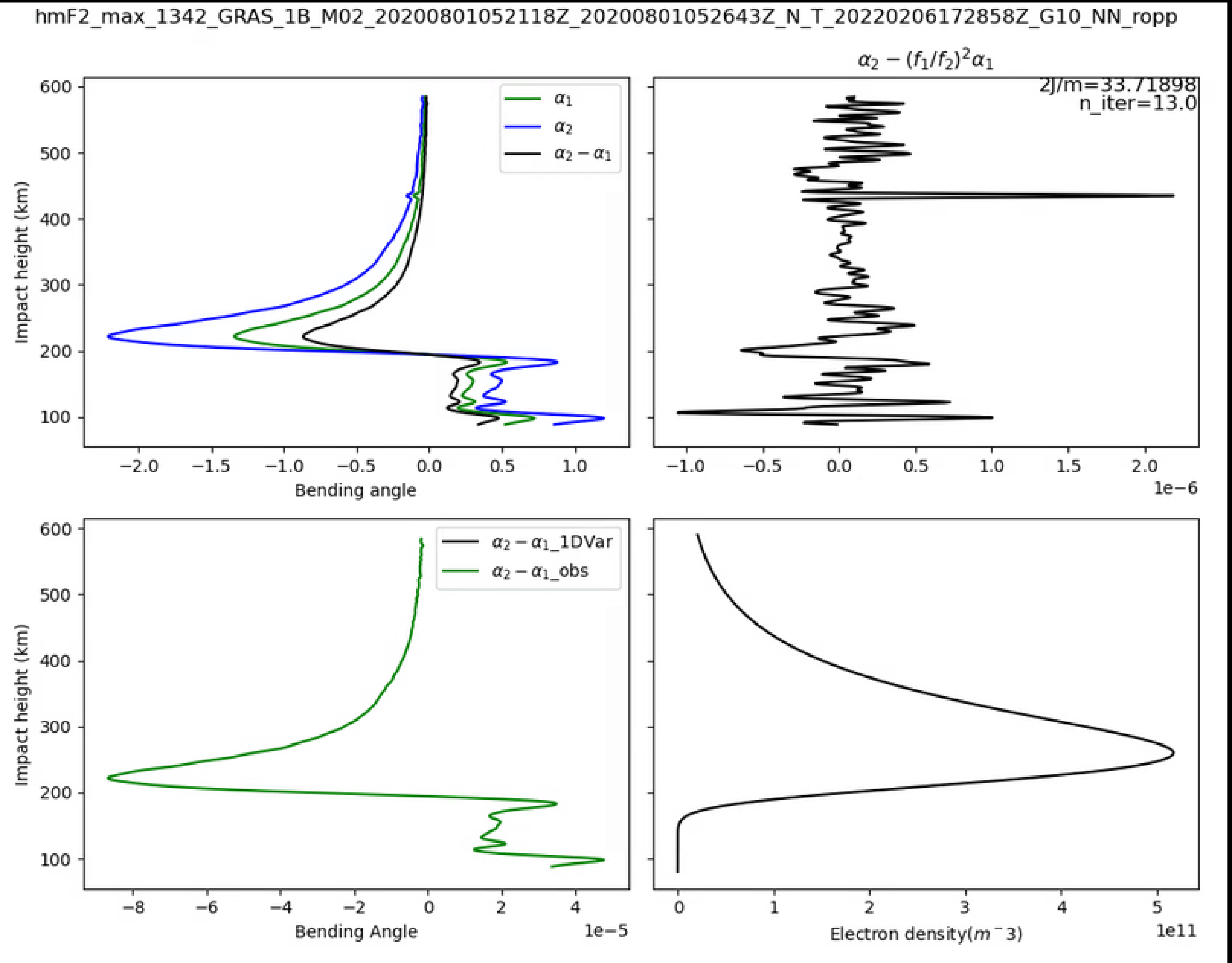




Bangle weights==1: 351
Percentage of bangles being used: 100.00%

Bangle weights==1: 114
Percentage of bangles being used: 28.43%

Case III: max hmF2>1300 km



- An absolutely 'normal' looking profile
- Passes the current QC checks ✓
- Probably an outlier, with hmF2>1300 km
- 1d var does not generate a solution

The log file...

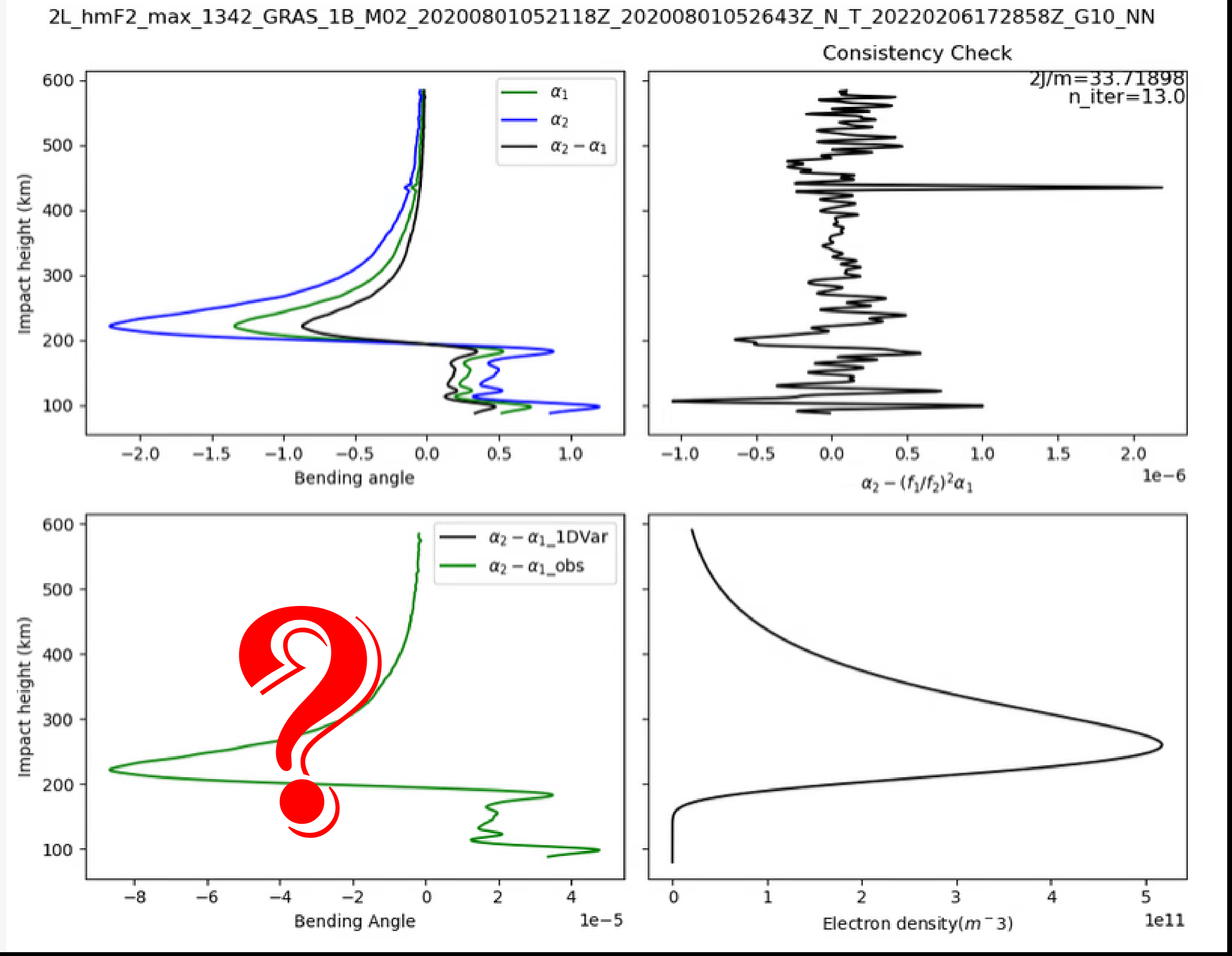
J = NaN

```
WARNING (from ropp_1dvar_levmarq_dbangle):  Levenberg-Marquardt solver returns ne_peak <= 0 ... resetting to 1% of background error.

      n_iter =    10    J = 6729.6            lambda -> 10.000

WARNING (from ropp_1dvar_levmarq_dbangle):  Levenberg-Marquardt solver returns ne_peak <= 0 ... resetting to 1% of background error.

      n_iter =    11    J = 5917.7            max(relative change in state) = 1.0000
      n_iter =    12    J = NaN               max(relative change in state) = 1.0000
      n_iter =    13    J = NaN               max(relative change in state) = 1.0000

INFO (from ropp_1dvar_levmarq_dbangle):  Convergence assumed to be achieved as the cost function did not change by more
    than 0.10000 for the last 2 iterations.

INFO (from ropp_1dvar_levmarq_dbangle):  Finished after 13 iterations (20 forward model / gradient evaluations).

INFO (from ropp_1dvar_levmarq_dbangle):  Scaled solution cost function 2J/m = 3.372E+01.

... (from ropp_1dvar_diagnostics):  Warning: 2J/m greater than  5.000. (niter = 13; 2J/m = 33.719)
INFO (from ropp_1dvar_dbangle):  Analysis VTEC = 52.635 TECU.
```

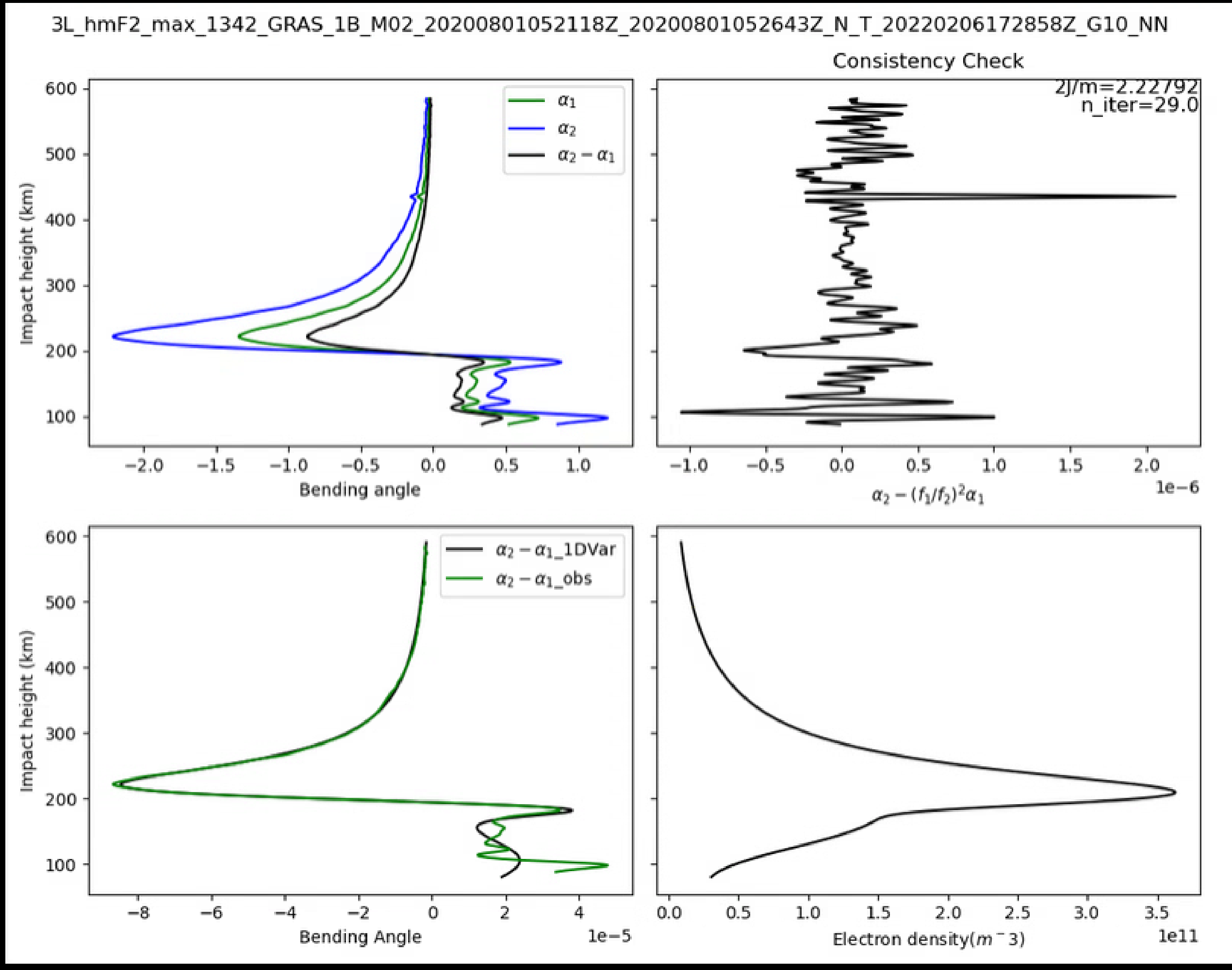
34 more cases with J= NaN for 3 layers ~ 0.14%

Case III: 3 layer analysis

Bangle weights==1: 351
Percentage of bangles being used: 100.00%



Bangle weights==1: 401
Percentage of bangles being used: 100.00%



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Other problematic cases

Criterion	ROPP 11 baseline	ROPP 11 improved_3 layer
Convergence is unlikely ***lambda_max = 1.0E10_wp***	1 case - Ropp 11 baseline_3 layer	-
iterations without achieving convergence **N_iter = 50**	-	***40/23990 -0.166%***
N_iter>=45	-	66 cases
J=NaN	18 cases - Ropp 11 baseline_2 layer	34 cases
hmF1 or hmF2 <100 km	1076 cases – ROPP 11 baseline 2 layer	tbc

2 layers – 3 layers Comparison Summary Diagnostics

Parameter	ROPP 11 baseline_2 layer 1 day	ROPP 11 updated_3 layer Full dataset
Mean 2J/m	7.9	4.647
2J/m>10	69 cases	1940 cases
Largest 2J/m	882	2103
N_iter>=40	9	139
% of problematic retrievals	15	8.66

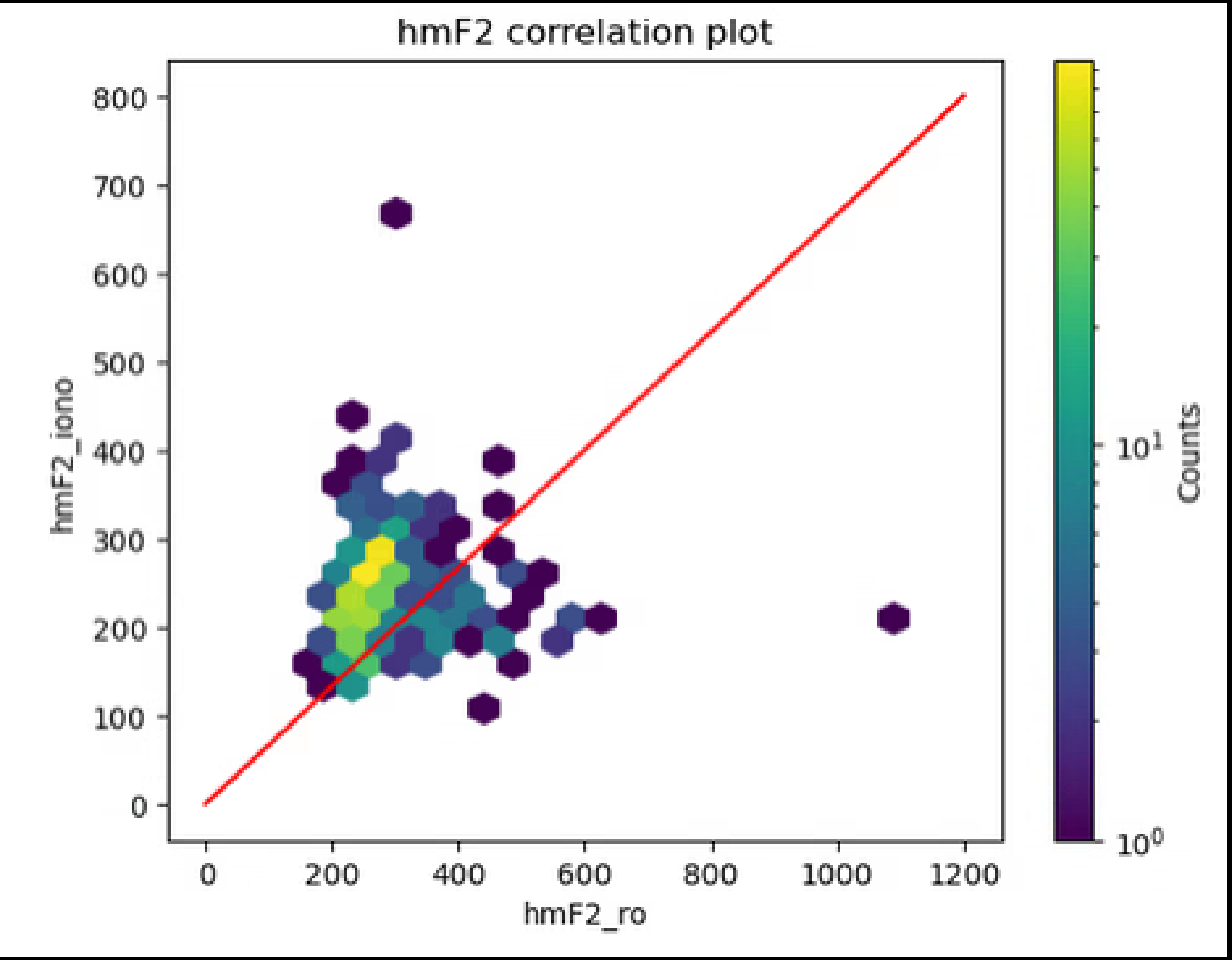
VALIDATION WITH IONOSONDE MEASUREMENTS (PRELIMINARY)

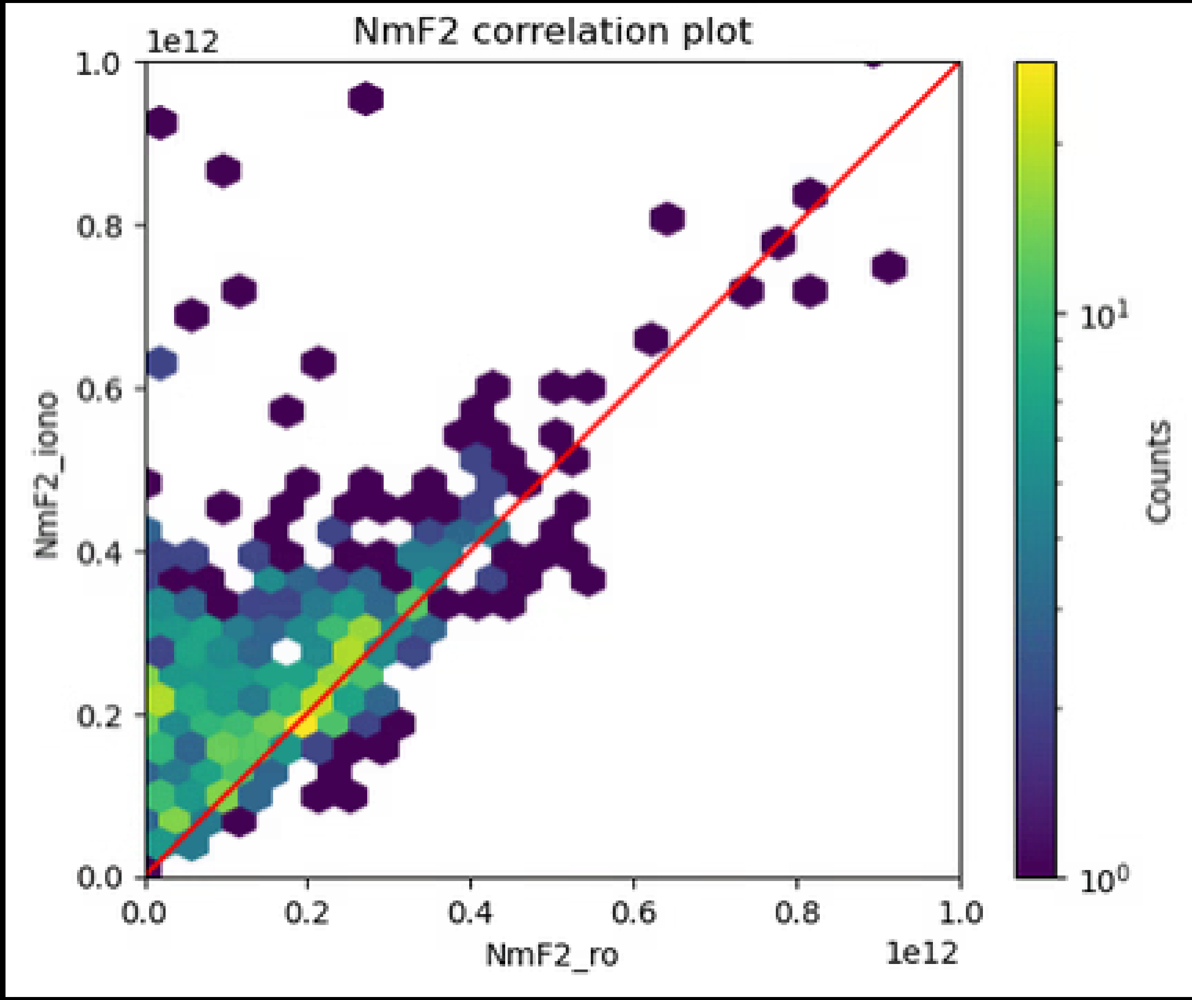
Ionosonde validation

- To validate RO data with ionosonde data to ensure that both measurement techniques provide consistent and accurate information about the ionospheric parameters.
- Improved accuracy and validation of observational data contribute to better predictions of ionospheric behaviour.
- Total 24k RO observations to collocate with ionosonde observations
- 52 unique ionosonde locations: Within 350 km and 2 hr we have 656 co-located occultations

Colocation criteria Dist/time/# of colocations	2hr	3 hr	4 hr
300 km	479	479	482
350 km	656	659	662

Nm and hm Correlation Plots





Summary and Future Work

- ROPP 11 ionospheric 1d var code has been successfully used to retrieve the ED profiles using MetOp A data that provides BA up to 600 km using2 and 3 layers.

- Only 8.66% of the total observations fail to converge in 50 iterations which does look like a good step forward

- Adding additional layers improves the performance of the 1d var
  - Next step: Improve the QC and test with 4 layers

- Validation of 1D var RO observations against Truth data - co-located Ionosonde retrievals – WiP

- Comparison with AVHIRO-2 model (coming soon!)

Thank you for your attention!

Abstract submission OPEN for

UK Space Weather & Space Environment Meeting II: Celebrating 10-years of 24/7 space-weather operational forecasting in the UK

Deadline: 14 June'24