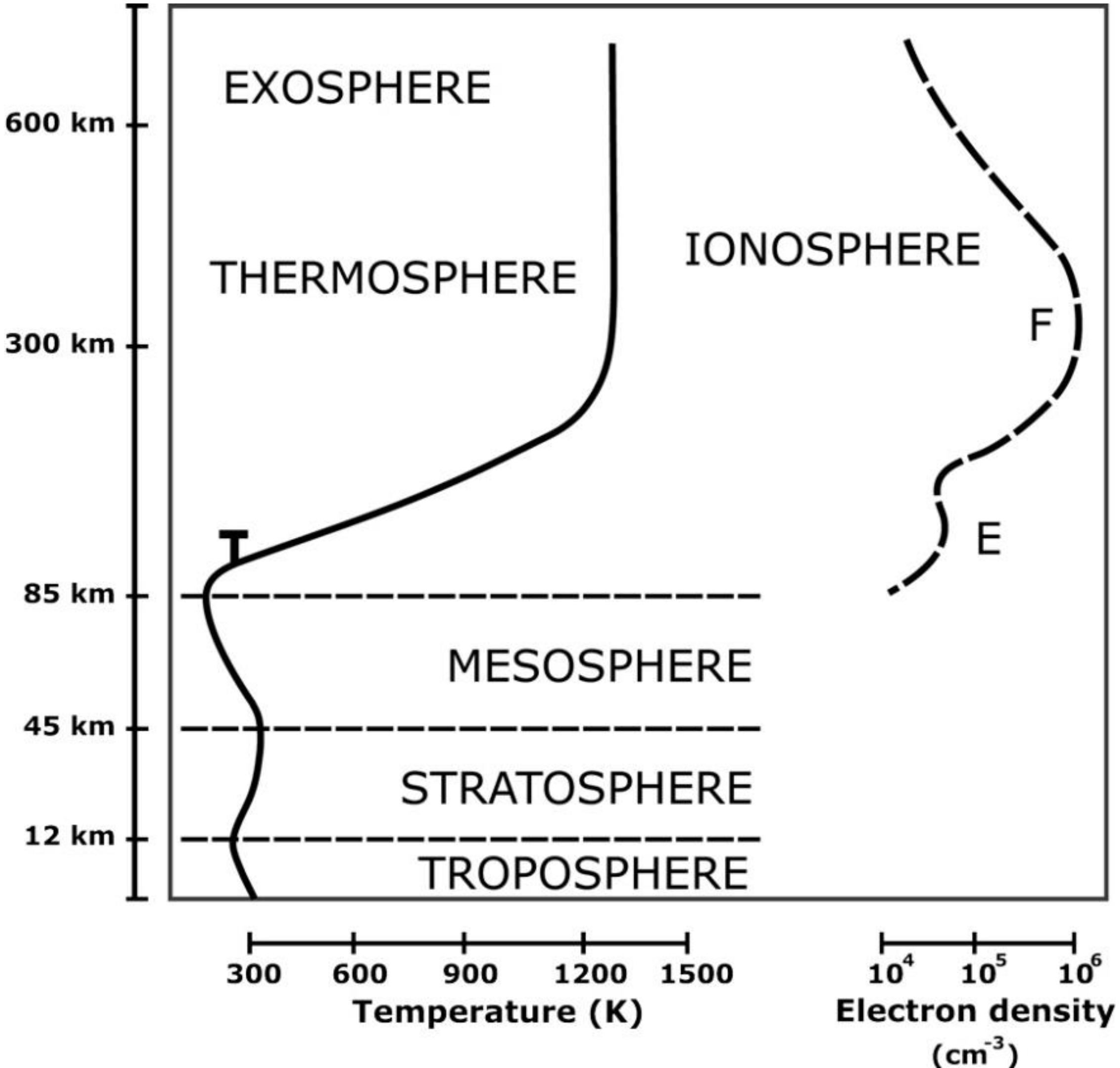
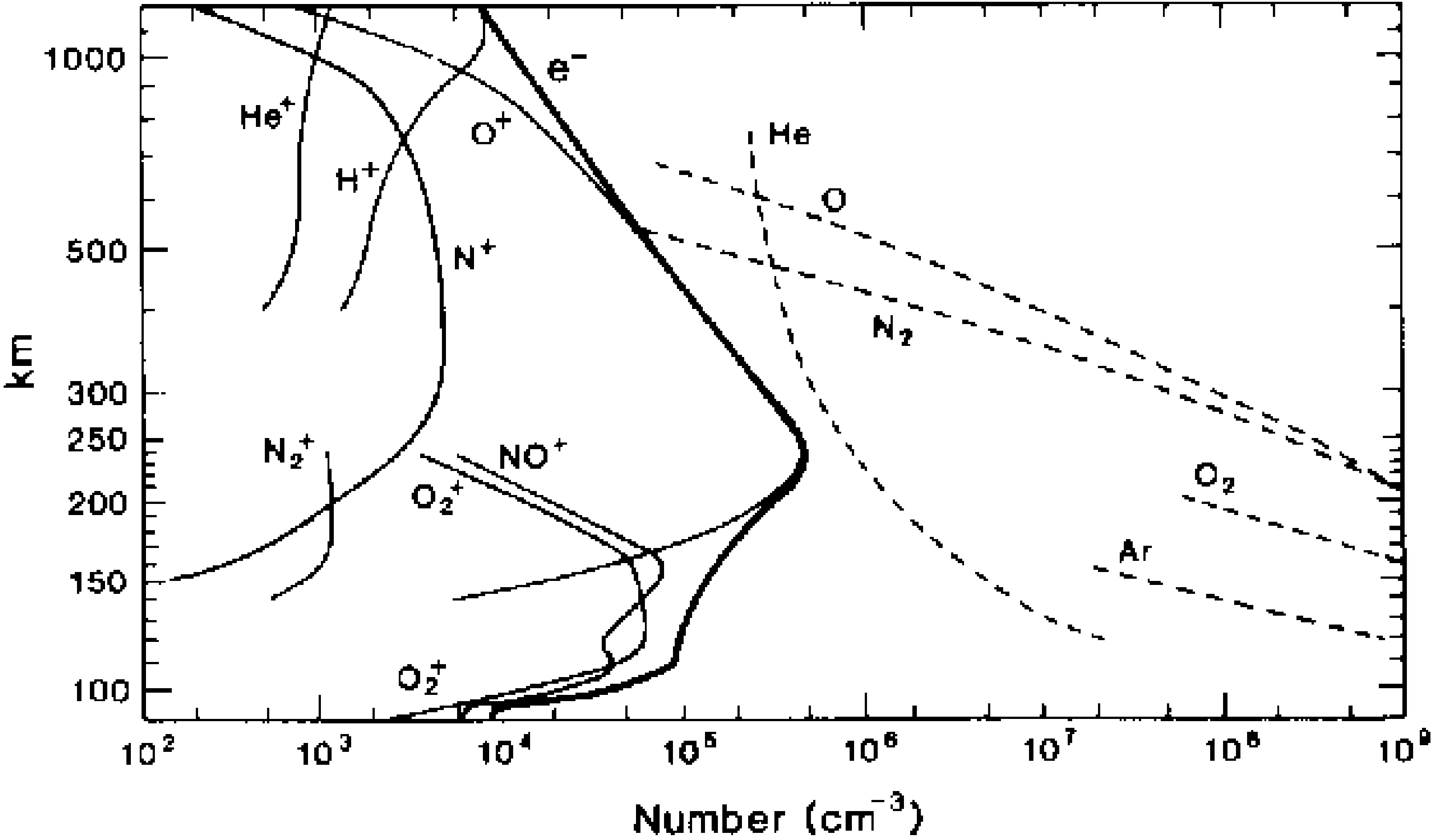
Assimilation of Radio Occultation Bending Angles in a Global Ionospheric Model

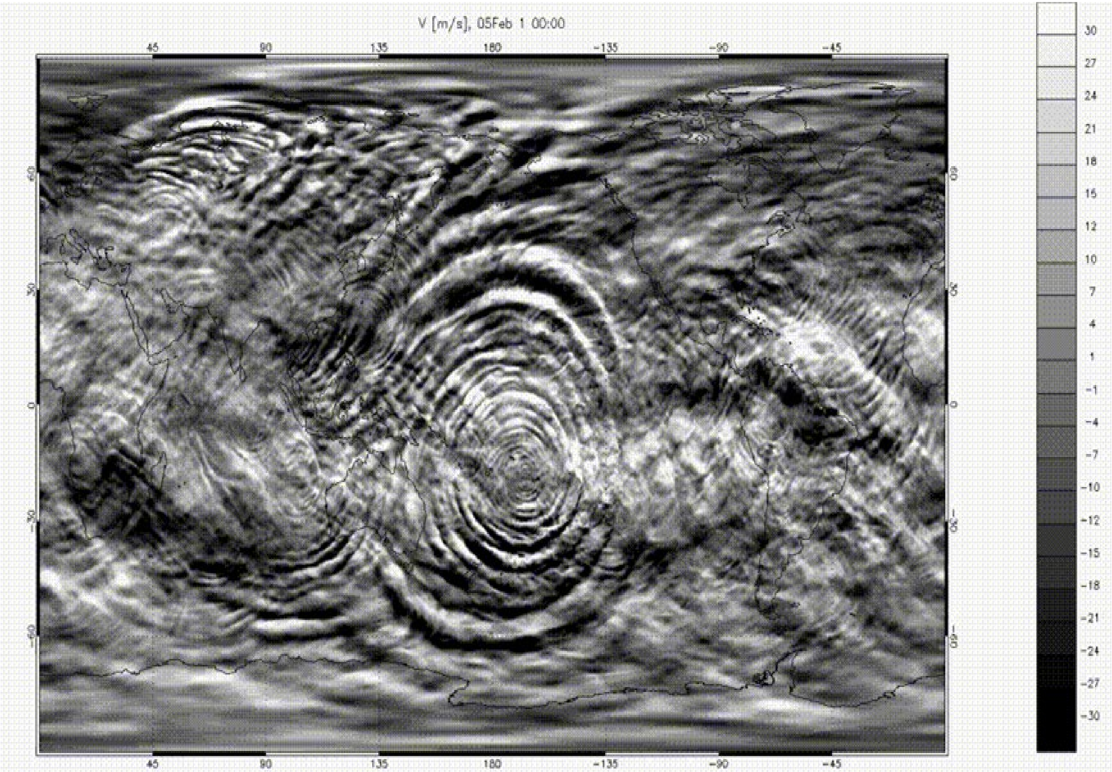
Sean Elvidge, Sean Healy, Ian Culverwell, David R. Themens

8th EUMETSAT ROM SAF Workshop on
GNSS RO Measurements
June 12, 2024


EXOSPHERE
THERMOSPHERE
IONOSPHERE
F
E
T
MESOSPHERE
STRATOSPHERE
TROPOSPHERE
600 km
300 km
85 km
45 km
12 km
300
600
900
1200
1500
Temperature (K)
10^4
10^5
10^6
Electron density
(cm^{-3})



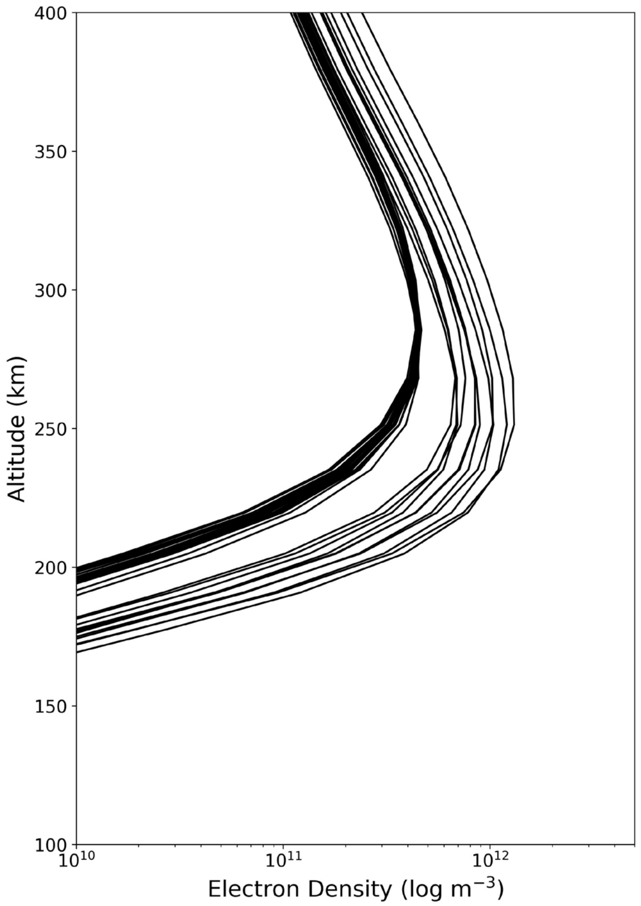
e⁻
He⁺
O⁺
He
H⁺
O
N⁺
N2
N2⁺
NO⁺
O2⁺
O2
Ar
O2⁺
km
1000
500
300
250
200
150
100
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
Number (cm^-3)



Courtesy of Tim Fuller-Rowell

UNIVERSITY OF BIRMINGHAM

SERENE SPACE ENVIRONMENT



Requirement for ionospheric modelling

- Many communication and navigation systems are affected by the ionosphere
  - Global Navigation Satellite Systems: GPS, Galileo, … (PNT)
  - Precise Point Positioning (PPP), e.g. convergence times
  - HF (e.g.):
    - Military and governmental communication systems
    - Aviation air-to-ground communications
    - Over the horizon radar (OTHR)
    - Amateur radio
    - Maritime services

- Median models are useful for planning
- But high-fidelity environmental specification, coupled with real time forecasting, is required to provide new functionality

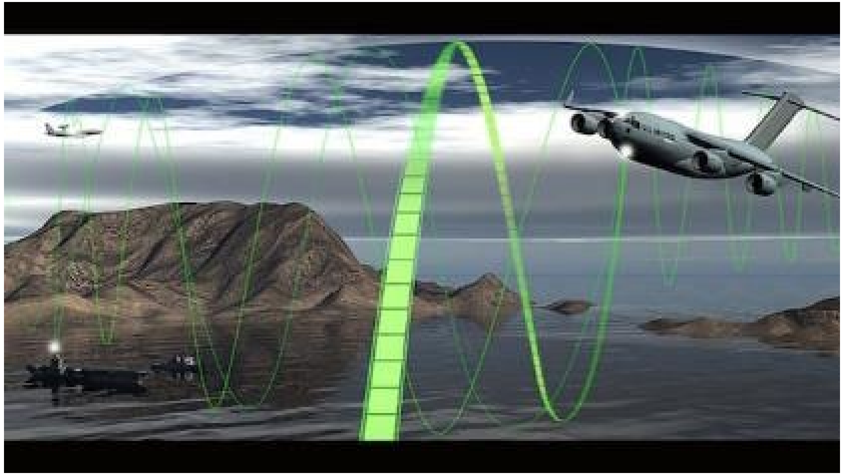
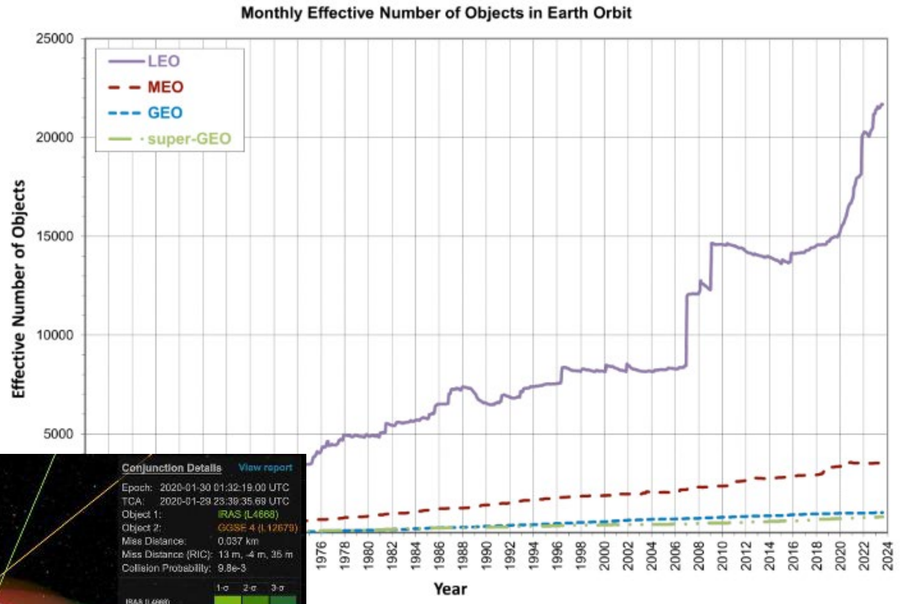


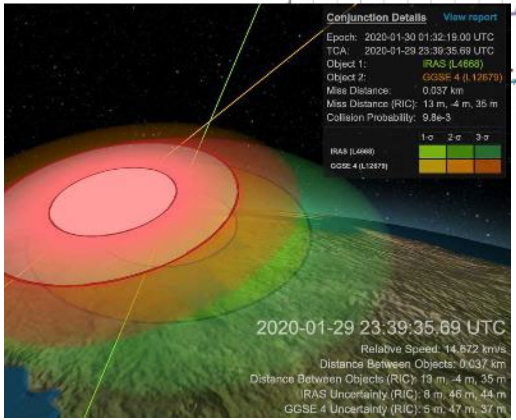
Photo: Rockwell Collins

UNIVERSITY OF BIRMINGHAM | SERENE SPACE ENVIRONMENT

Requirement for thermospheric modelling

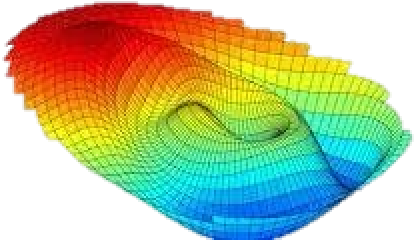
- Collision avoidance among orbiting satellites has become a routine task in space operations
- In Low Earth Orbit (LEO; < 2,000 km) the largest unknown in orbit determination is atmospheric drag
- Impacts on
    - Orbital propagation
    - Collision avoidance
    - Re-entry prediction
    - Lifetime estimation

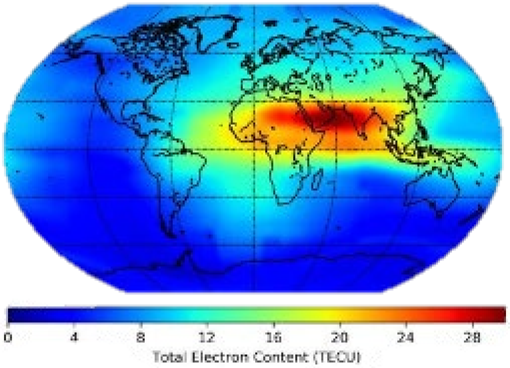




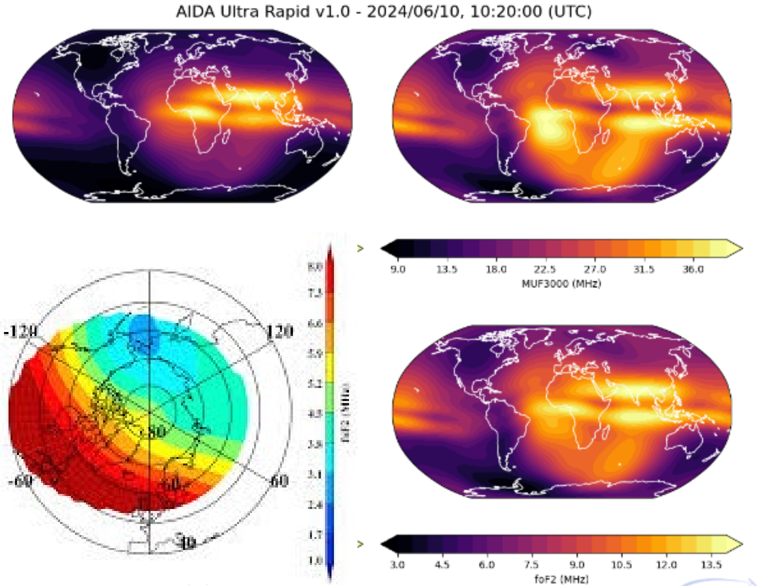
UNIVERSITY OF BIRMINGHAM | SERENE SPACE ENVIRONMENT

SERENE's Upper Atmosphere Models





- AENeAS
  - The **A**dvanced **E**nsemble **Ne**tworked **A**ssimilation **S**ystem
- E-/A-CHAIM
  - The **E**mpirical/**A**ssimilation – **C**anadian **H**igh **A**rctic **I**onospheric **M**odel
- AIDA
  - The **A**dvanced **I**onospheric **D**ata **A**ssimilation model

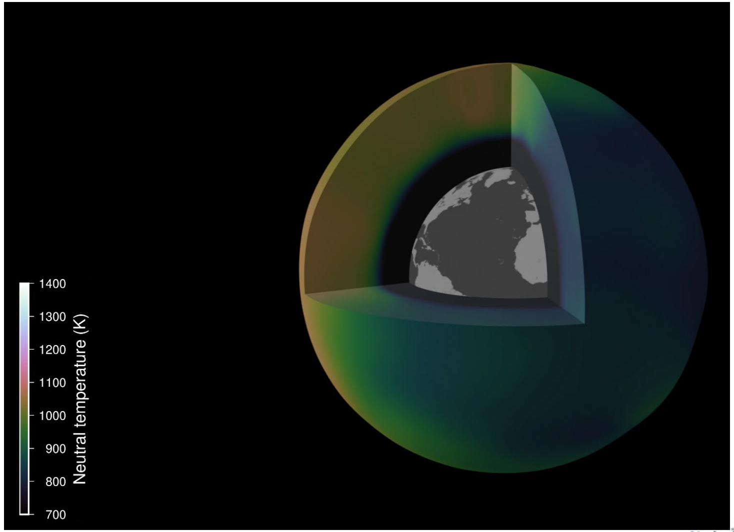


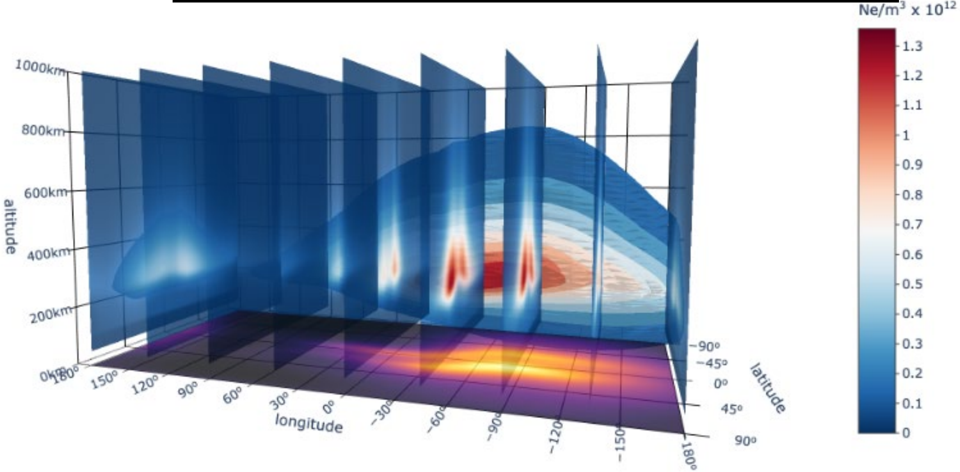
AENeAS

- A realtime upper atmosphere data assimilation model
  - Based on solving the underlying physics of the system and fusing with observations
  - Variant of the ensemble Kalman filter (LETKF)
- Provides:
  - Probabilistic nowcasts and forecasts (with uncertainties)
    - Not necessarily Gaussian
  - Runs operationally at UK Met Office (output available from Q4 2024)

UNIVERSITY OF BIRMINGHAM | SERENE SPACE ENVIRONMENT

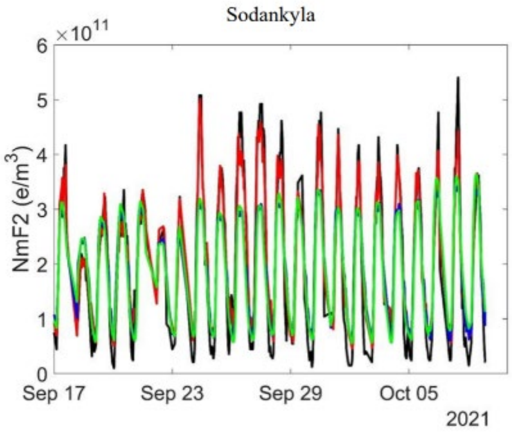
Neutral temperature at model "lid"





E-/A-CHAIM

- E-CHAIM:
  - Empirical model of high latitude (> 50˚N geomagnetic latitude) ionospheric electron density
  - Primarily climatology, but also includes intermediate timescale variability (1 to 30 day-timescale variations)
  - Includes electron precipitation, D-Region, Solar Energetic Protons (PCA)
  - Openly available source code: http://e-chaim.chain-project.net/
  - Designed to support Over-the-Horizon Radar (OTHR) and HF radio propagation operations at high latitudes.
- A-CHAIM:
  - Auxiliary particle filter data assimilation scheme that uses E-CHAIM as its background model.
  - Freely available output: https://a-chaim.chain-project.net/
  - System run every hour. Reanalysis of last three hours and two hour forecast.

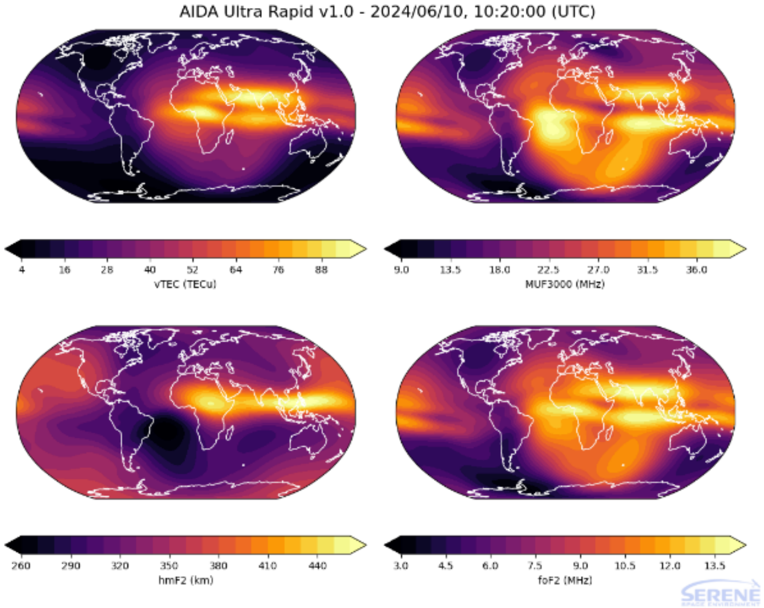


UNIVERSITY OF BIRMINGHAM | SERENE SPACE ENVIRONMENT

AIDA

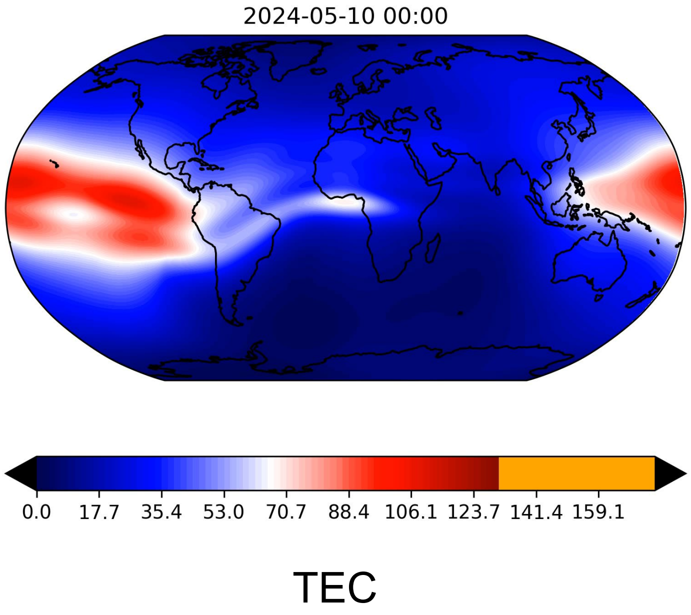
- Global particle filter which uses NeQuick as its background model
  - Model state space built using the parameterized vertical structure, with spherical harmonics for the horizontal perturbations makes it relatively small

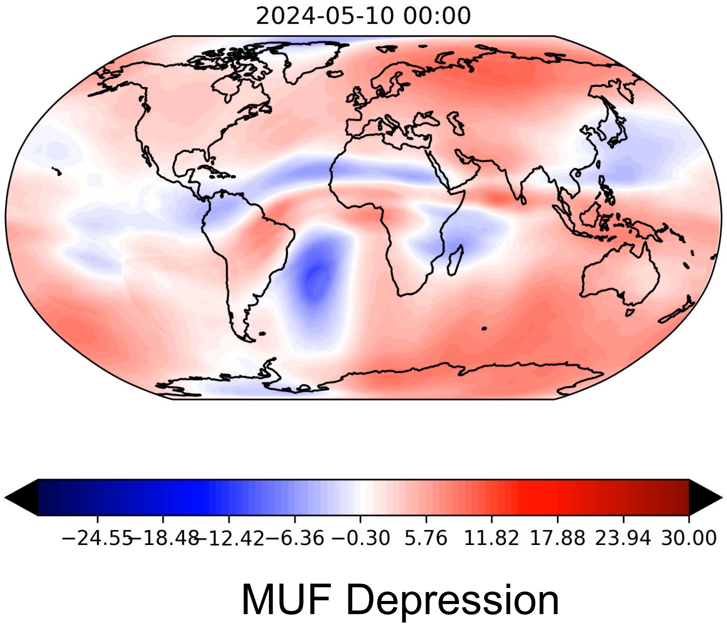
Name	Time resolution	Latency	Expected assimilated observations
Ultra-Rapid	5 min	5 min	NTRIP GNSS
Rapid	5 min	90 min	GNSS (partial), Ionosonde (partial)
Final	5 min	Daily	GNSS, Ionosonde, RO



serene.bham.ac.uk

AIDA – May '24 Storm

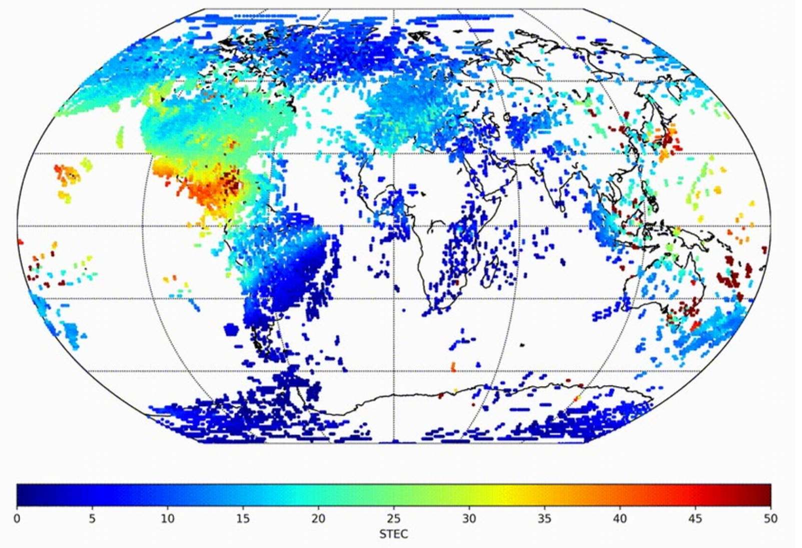




UNIVERSITY OF BIRMINGHAM | SERENE SPACE ENVIRONMENT

Observations Used by the Models

- Electron density
    - Slant TEC (STEC) from GNSS satellites
    - Vertical TEC (VTEC) from altimeter satellites
    - Vertical profiles from ionosondes (true heights)
        - [Over 30 million observations used to build empirical model]
    - Radio Occultation
        - $\delta STEC/\delta a$ (bending angle difference) assimilation
        - [Over 1 million observations used for empirical model]
- Total neutral density
    - From CHAMP/GRACE/Swarm (processed)
    - Two-line elements (derived)

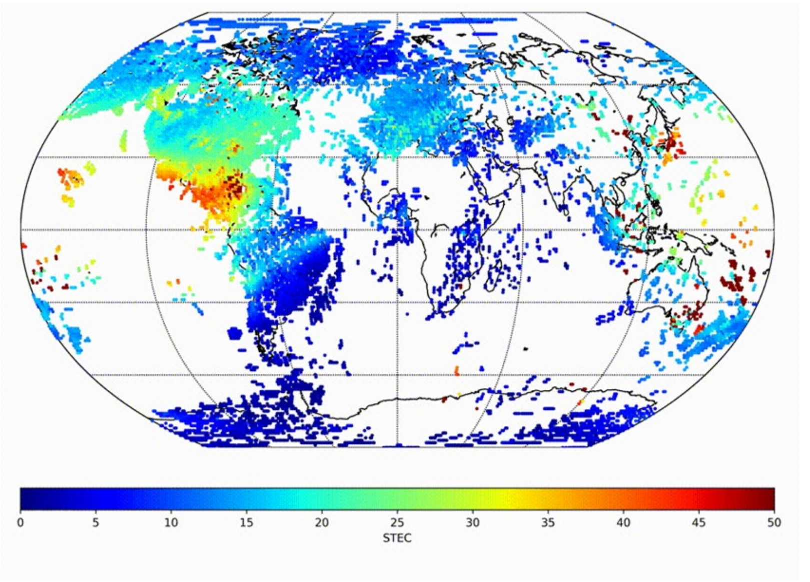


UNIVERSITY OF BIRMINGHAM

SERENE SPACE ENVIRONMENT

Observations Used by the Models

- Electron density
  - Slant TEC (STEC) from GNSS satellites
  - Vertical TEC (VTEC) from altimeter satellites
  - Vertical profiles from ionosondes (true heights)
    - [Over 30 million observations used to build empirical model]
  - **Radio Occultation**
    - $\delta STEC/\delta a$ **(bending angle difference) assimilation**
    - **[Over 1 million observations used for empirical model]**
- Total neutral density
  - From CHAMP/GRACE/Swarm (processed)
  - Two-line elements (derived)



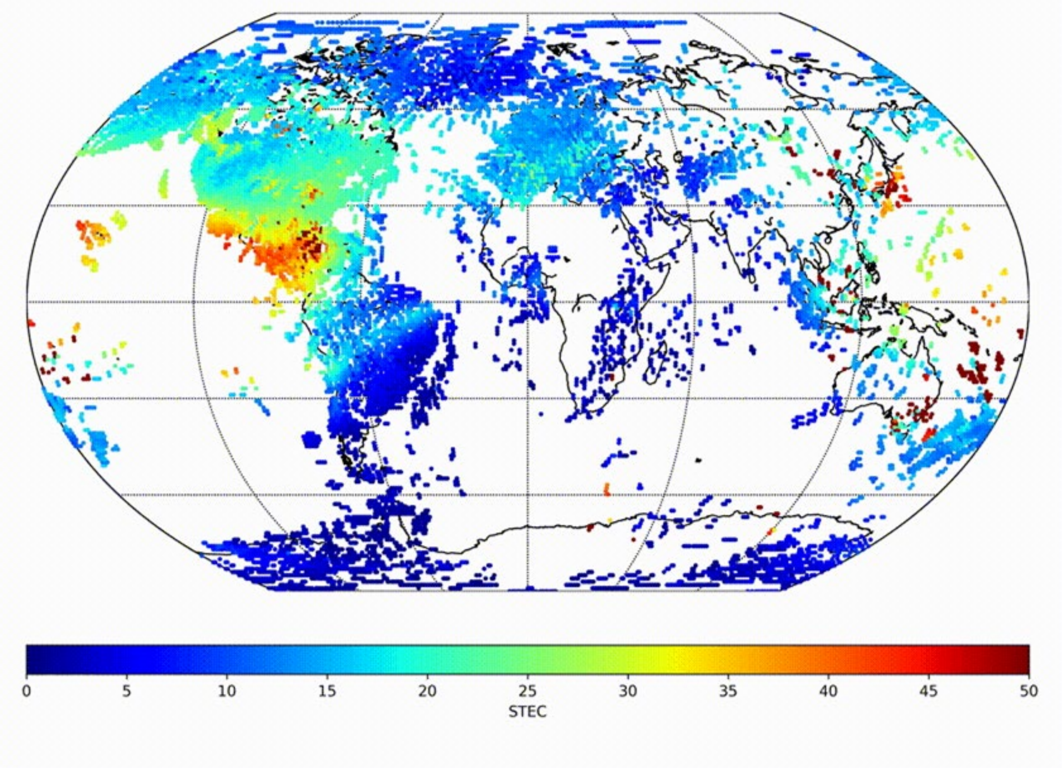
UNIVERSITY OF BIRMINGHAM

SERENE SPACE ENVIRONMENT

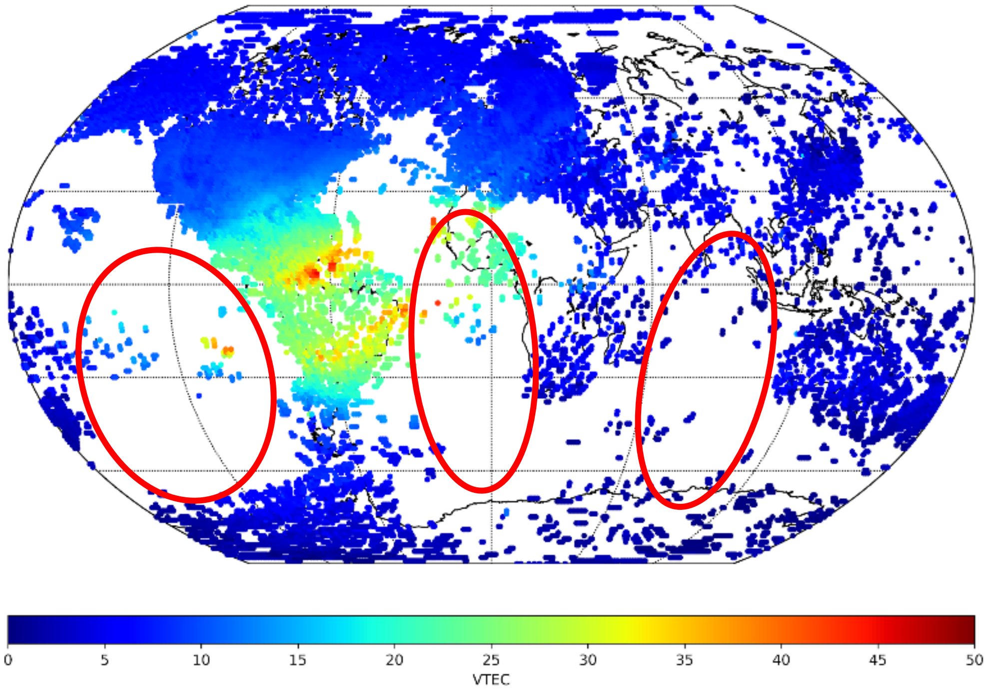
E-CHAIM: Radio Occultation Data

- CHAMP, GRACE, and COSMIC GPS Radio Occultation electron density profiles
- Gathered all profiles from above 45N geomagnetic latitude (~1,000,000 profiles)
- Profiles with negative values anywhere above 100 km are discarded
- Noise-dominant profiles are identified and removed by evaluating RMS errors with respect to a fitted Vary-Chap profile
- Profiles with multiple maxima are removed

Assimilated TEC Observations



Assimilated TEC Observations



UNIVERSITY OF BIRMINGHAM | SERENE SPACE ENVIRONMENT

Assimilated TEC Observations

- TEC is the most used observation in ionospheric data assimilation models
- Biggest challenge when assimilating TEC is to estimate the differential code biases (DCBs)
  - Pseudorange observations are affected by signal and frequency dependent biases
  - Whilst CODE (Center for Orbit Determination in Europe) provides some estimated DCBs, in general these have to be solved for in the data assimilation scheme

Assimilated TEC Observations

- TEC is the most used observation in ionospheric data assimilation models
- Biggest challenge when assimilating TEC is to estimate the differential code biases (DCBs)
    - Pseudorange observations are affected by signal and frequency dependent biases
    - Whilst CODE (Center for Orbit Determination in Europe) provides some estimated DCBs, in general these have to be solved for in the data assimilation scheme

- It has been shown that the derivative of TEC, with respect to the impact parameter, $(\delta STEC/\delta a)$, can be used in a 1D-Var scheme for retrieval of profiles from RO observations

Space Weather

RESEARCH ARTICLE

One-Dimensional Variational Ionospheric Retrieval Using Radio Occultation Bending Angles: 1. Theory

I. D. Culverwell[1], S. B. Healy[2], and S. Elvidge[3]

Abstract A new one dimensional variational (1D Var) retrieval method for ionospheric GNSS radio occultation (GNSS RO) measurements is described. The forward model implicit in the retrieval calculates the bending angles produced by a one-dimensional ionospheric electron density profile, modeled with multiple "Vary-Chap" layers. It is demonstrated that gradient based minimization techniques can be applied to this retrieval problem. The use of ionospheric bending angles is discussed. This approach circumvents the need for Differential Code Bias (DCB) estimates when using the measurements. This new, general retrieval method is applicable to both standard GNSS-RO retrieval problems, and the truncated geometry of EUMETSAT's Metop Second Generation (Metop-SG), which will provide GNSS-RO measurements up to about 600 km above the surface. The climatological a priori information used in the 1D-Var is effectively a starting point for the 1D-Var minimization, rather than a strong constraint on the final solution. In this paper the approach has been tested with 143 COSMIC 1 measurements. We find that the method converges in 135 of the cases, but around 25 of those have high "cost at convergence" values. In the companion paper (Elvidge et al., 2023), a full statistical analysis of the method, using over 10,000 COSMIC-2 measurements, has been made.

Plain Language Summary This paper presents a new way of estimating the density of electrons in the ionosphere—the part of the Earth's atmosphere in which atoms are ionized by radiation from the Sun. Radio signals sent between GNSS navigational satellites and receivers in a low orbit around the Earth are delayed, and their paths are bent, by the presence of electrons in the ionosphere. Previous attempts to use these observations to estimate the electron density have been based on the delay of the signals. The new approach outlined in this paper uses the bending incurred by the radio waves instead. Such "bending angles" have been used to infer some properties of the lower atmosphere for many years, and are widely available. We demonstrate that by extending these measurements to greater heights, they can provide useful information about the ionosphere as well.

Received 26 MAY 2023

One-Dimensional Variational Ionospheric Retrieval Using Radio Occultation Bending Angles: 2. Validation

S. Elvidge[1], S. B. Healy[2], and I. D. Culverwell[3]

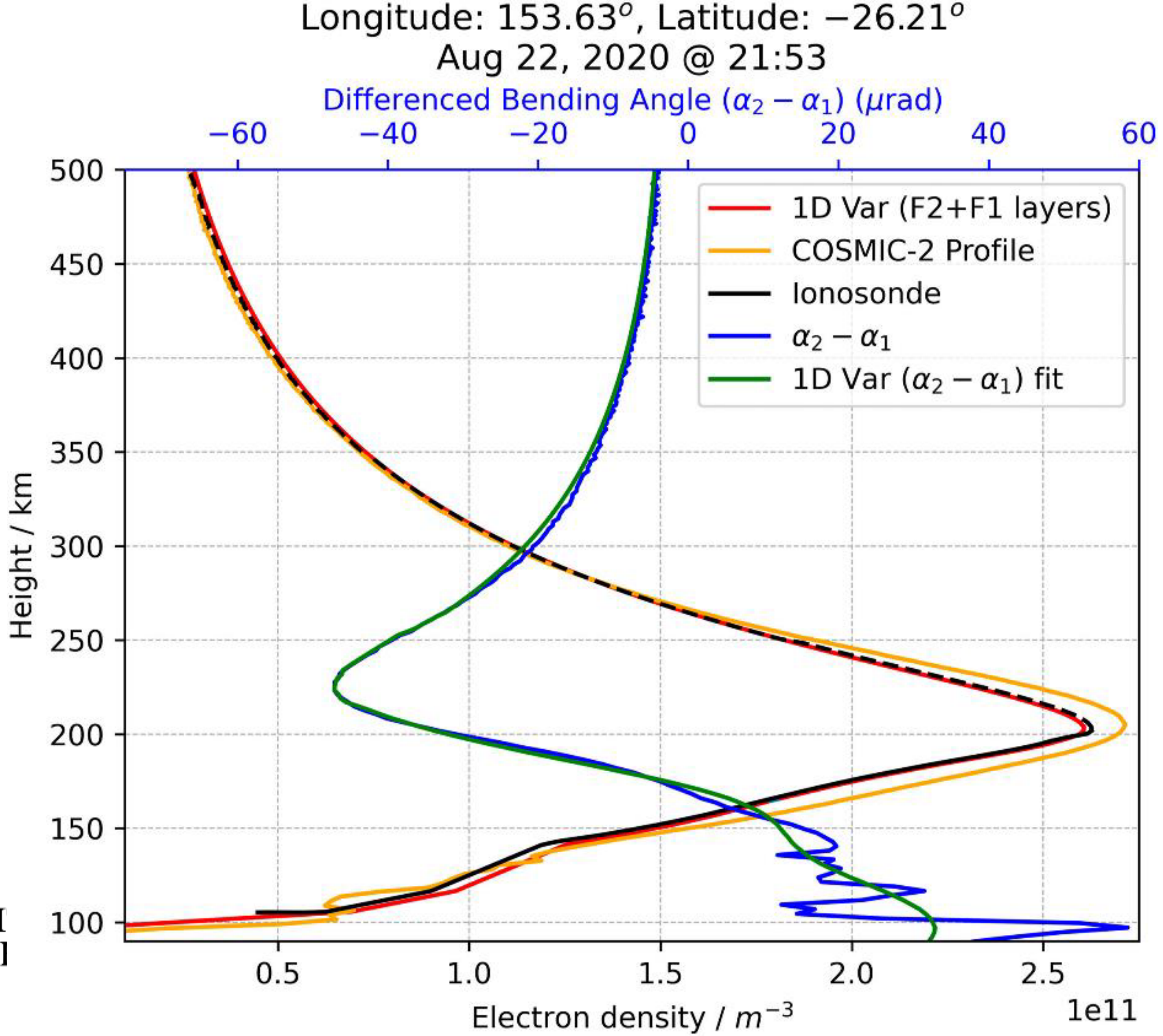
[1]Space Environment and Radio Engineering (SERENE), University of Birmingham, Birmingham, UK, [2]European Centre for Medium-Range Weather Forecasts, Reading, UK, [3]Met Office, Exeter, UK

Abstract Culverwell et al. (2023, https://doi.org/10.1029/2023SW003572) described a new one-dimensional variational (1D-Var) retrieval approach for ionospheric GNSS radio occultation (GNSS-RO) measurements. The approach maps a one-dimensional ionospheric electron density profile, modeled with multiple "Vary-Chap" layers, to bending angle space. This paper improves the computational performance of the 1D Var retrieval using an improved background model and validates the approach by comparing with the COSMIC-2 profile retrievals, based on an Abel Transform inversion, and co-located (within 200 km) ionosonde observations using all suitable data from 2020. A three or four layer Vary-Chap in the 1D-Var retrieval shows improved performance compared to COSMIC-2 retrievals in terms of percentage error for the F2 peak parameters (NmF2 and hmF2). Furthermore, skill in retrieval (compared to COSMIC-2 profiles) throughout the bottomside (~90–300 km) has been demonstrated. With a single Vary-Chap layer the performance is similar, but this improves by approximately 40% when using four-layers.

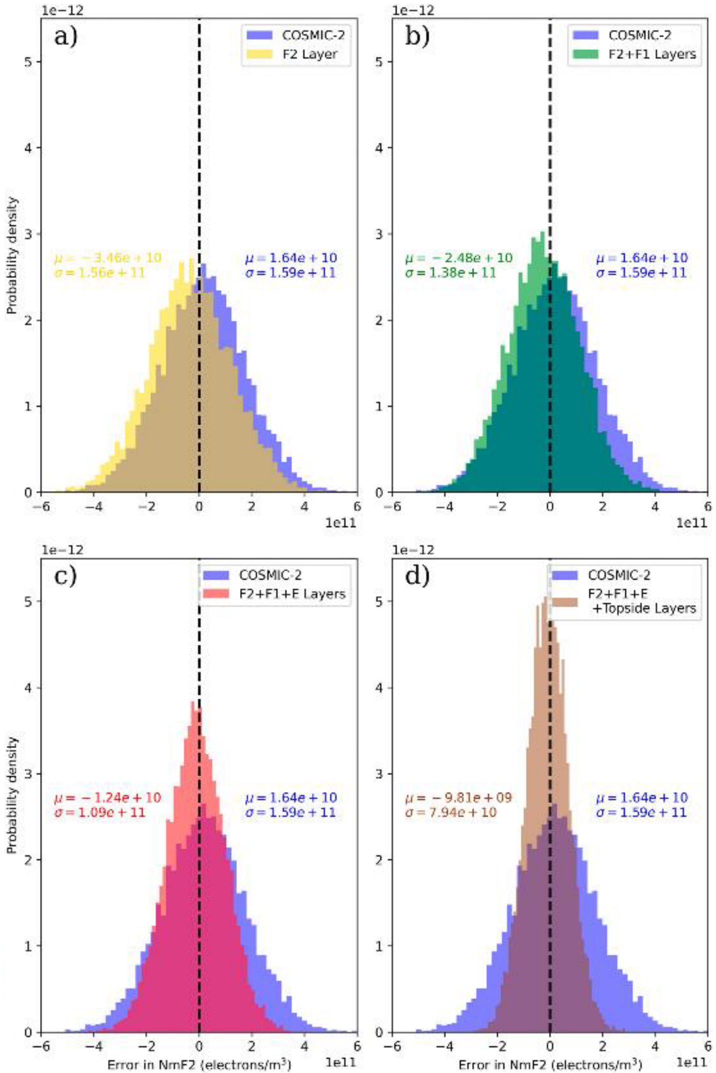
Plain Language Summary Culverwell et al. (2023, https://doi.org/10.22541/essoar.168614409.98641332) presented a new way of estimating ionospheric electron density using the amount of bending experienced by GNSS signals in the upper atmosphere. In this paper, as well as providing extensive validation of the technique, the computational performance is improved by using better initial conditions. The validation is done by comparing the newly described approach with the method used by the COSMIC-2 satellite constellation using additional data from ground-based sensors known as ionosondes. The newly described technique is found to provide improvements of approximately 40% compared to a complementary approach using by COSMIC-2.

Received 26 MAY 2023
Accepted 29 OCT 2023

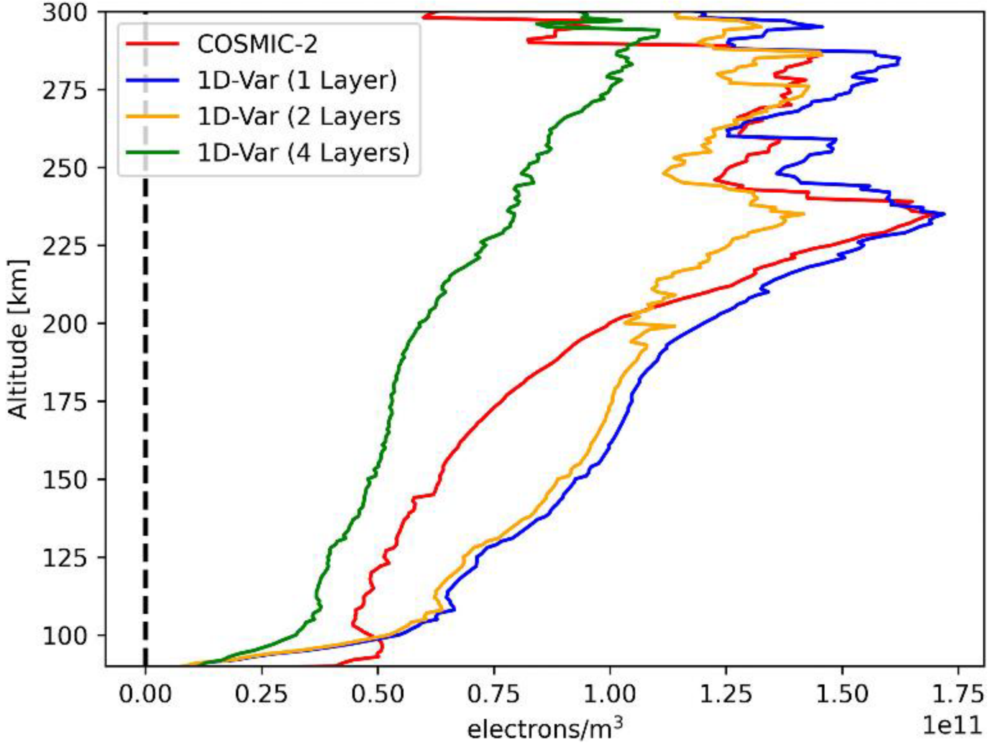
UNIVERSITY OF BIRMINGHAM | SERENE SPACE ENVIRONMENT



UNIVERSI
BIRMINGI



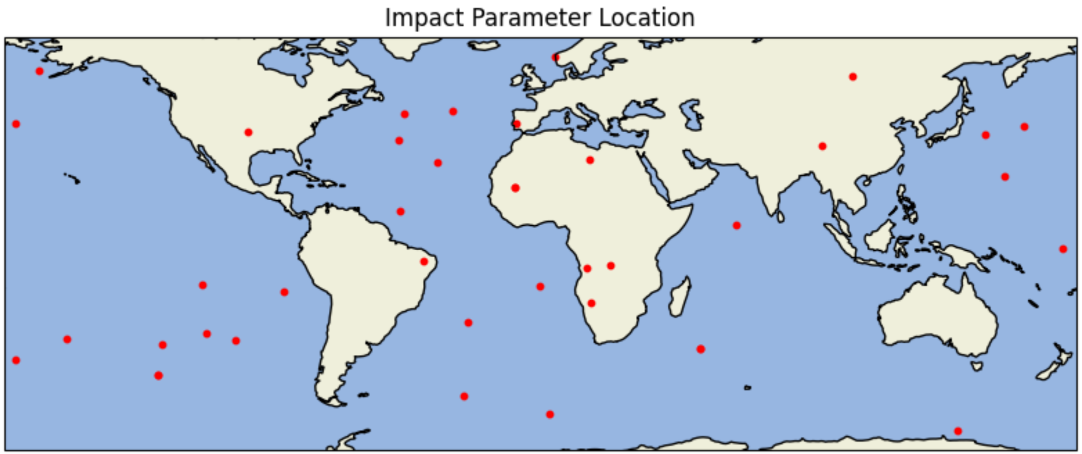
a)
COSMIC-2
F2 Layer
$\mu = -3.46e+10$
$\sigma = 1.56e+11$
$\mu = 1.64e+10$
$\sigma = 1.59e+11$
b)
COSMIC-2
F2+F1 Layers
$\mu = -2.48e+10$
$\sigma = 1.38e+11$
$\mu = 1.64e+10$
$\sigma = 1.59e+11$
c)
COSMIC-2
F2+F1+E Layers
$\mu = -1.24e+10$
$\sigma = 1.09e+11$
$\mu = 1.64e+10$
$\sigma = 1.59e+11$
d)
COSMIC-2
F2+F1+E +Topside Layers
$\mu = -9.81e+09$
$\sigma = 7.94e+10$
$\mu = 1.64e+10$
$\sigma = 1.59e+11$
Probability density
1e-12
1e11
Error in NmF2 (electrons/m^3)



COSMIC-2
1D-Var (1 Layer)
1D-Var (2 Layers)
1D-Var (4 Layers)
Altitude [km]
electrons/m^3
1e11

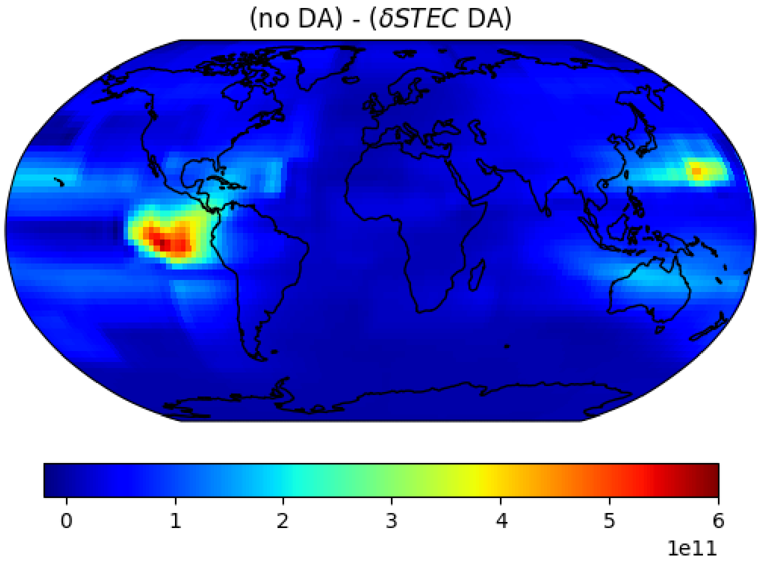
Example Assimilation in AENeAS

- Assimilation of COSMIC RO bending angles in AENeAS using three different approaches:
  1. COSMIC provided DCBs
  2. DCBs estimated in Kalman Filter state vector
  3. Assimilation without DCBs ($\delta STEC/\delta a$)

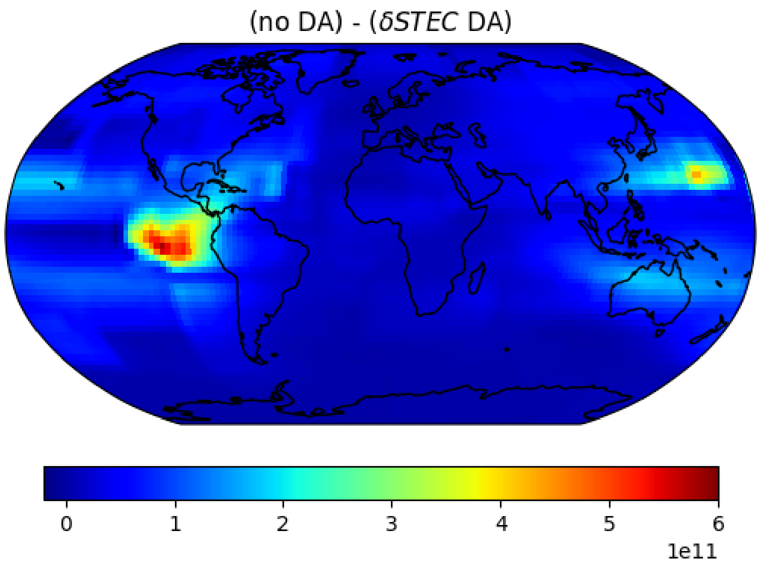


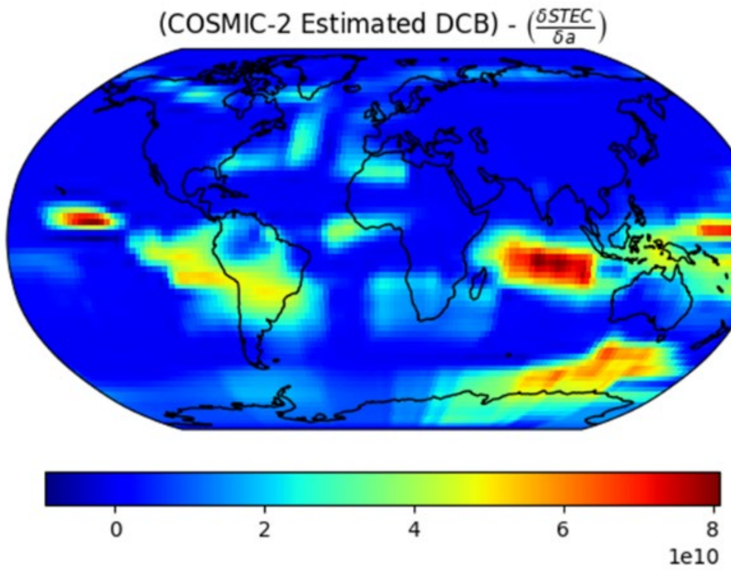
UNIVERSITY OF BIRMINGHAM | SERENE SPACE ENVIRONMENT

AENeAS output difference maps (NmF2)

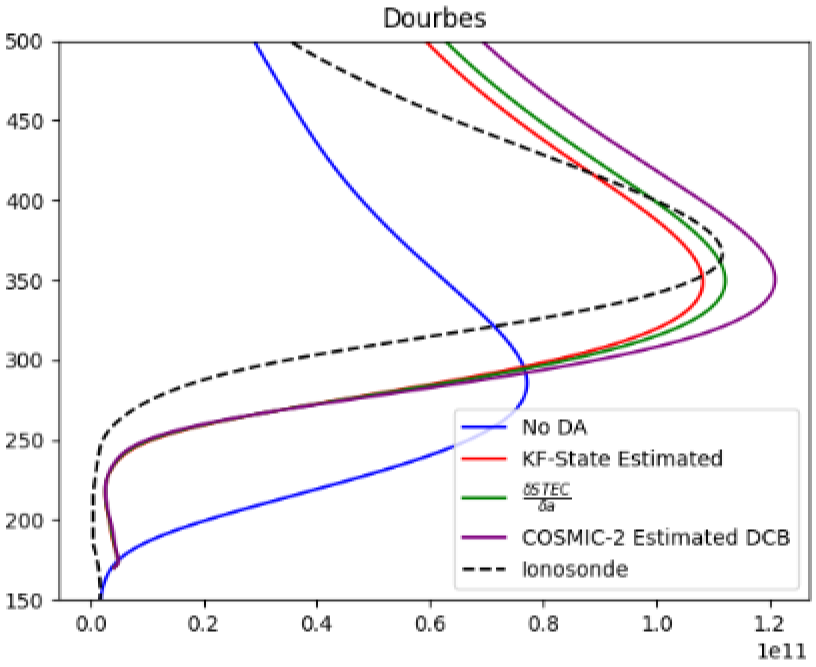


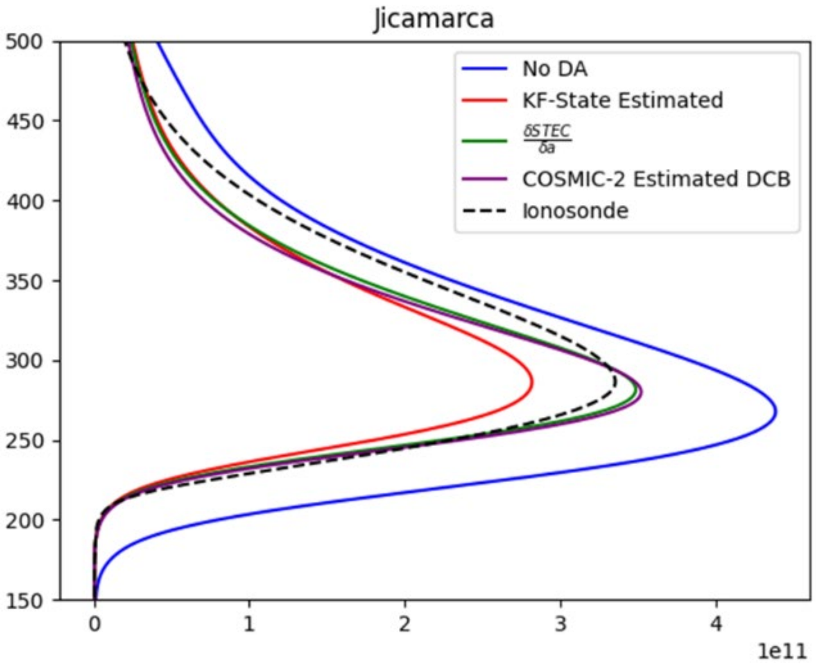
AENeAS output difference maps (NmF2)



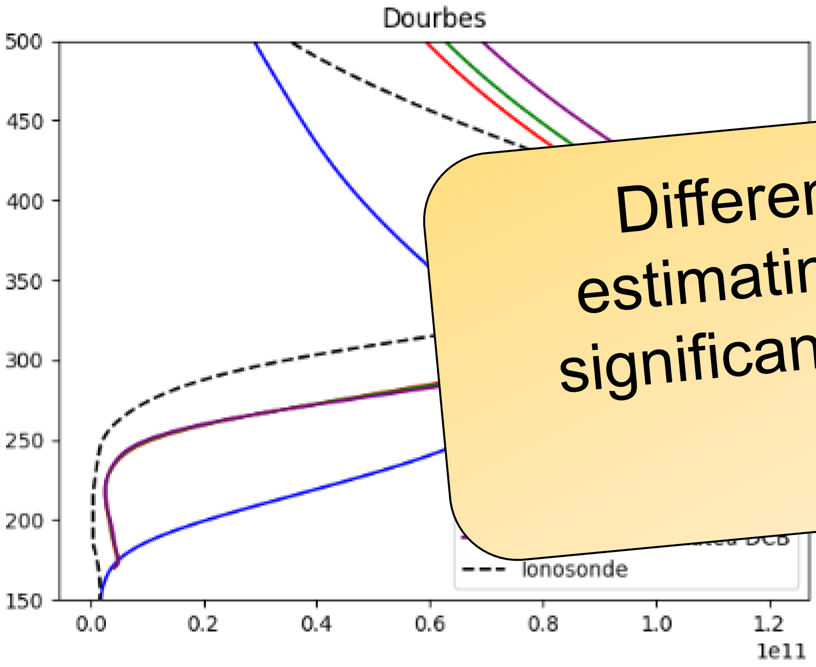


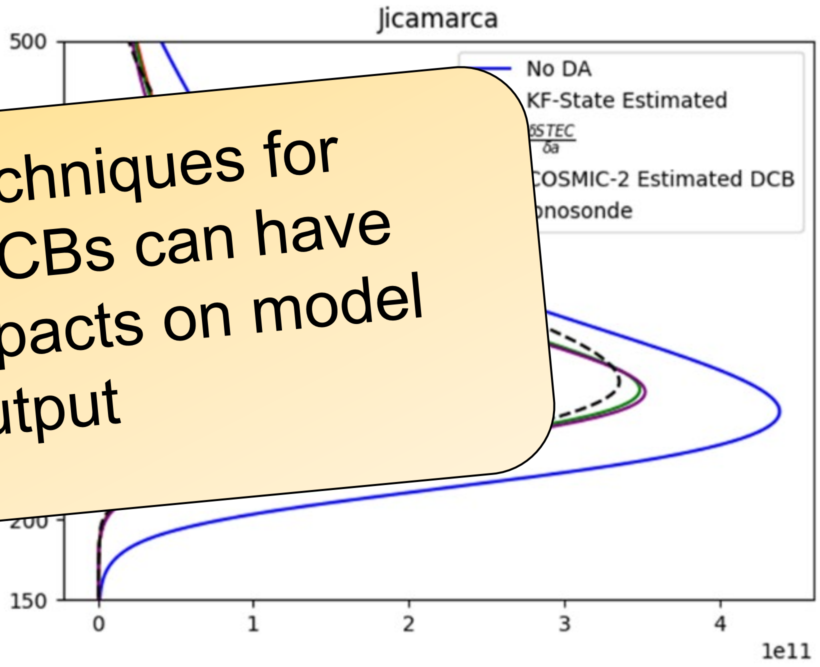
UNIVERSITY OF BIRMINGHAM | SERENE SPACE ENVIRONMENT





Thanks to David Themens for hand scaling the ionosondes





Different techniques for estimating DCBs can have significant impacts on model output

Thanks to David Themens for hand scaling the ionosondes

Our Next Steps with RO

- Formally include $\delta STEC/\delta a$ assimilation in AENeAS (more than just this simple example!), undertake statistical validation compared to alternative methods

Our Next Steps with RO

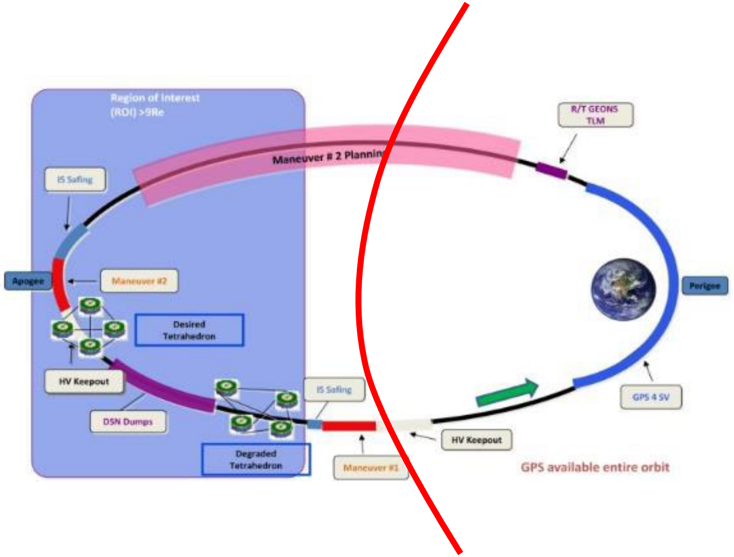
- Formally include $\delta STEC/\delta a$ assimilation in AENeAS (more than just this simple example!), undertake statistical validation compared to alternative methods

- Routine assimilation of near-realtime RO in AIDA
  - Ultra-Rapid: 5 mins
  - Rapid: 90 minutes

UNIVERSITY OF BIRMINGHAM | SERENE SPACE ENVIRONMENT

Our Next Steps with RO

- Formally include $\delta STEC/\delta a$ assimilation in AENeAS (more than just this simple example!), undertake statistical validation compared to alternative methods
- Routine assimilation of near-realtime RO in AIDA
  - Ultra-Rapid: 5 mins
  - Rapid: 90 minutes
- Magnetospheric Multiscale (MMS) Mission
  - Perigee: 2,550 km
  - Apogee: 70,080 km / 152,900 km
  - GPS through entire orbit
    - Potential unprecedented data of plasmasphere



UNIVERSITY OF BIRMINGHAM | SERENE SPACE ENVIRONMENT

UNIVERSITY OF BIRMINGHAM

SERENE

SPACE ENVIRONMENT