Assimilation of total electron content in a SAMI3 simulation

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Abstract

Total electron content (TEC) observations can provide insights into electron density variations in the ionosphere. Such variations are associated with many aspects of ionospheric dynamics, including traveling ionospheric disturbances. In the present work we assimilate observations of TEC and horizontal TEC gradients into the SAMI3 (SAMI3 is Another Model of the Ionosphere 3D) ionosphere model. Assimilation into SAMI3 is accomplished using an ensemble Kalman filter implemented within LightDA, an extensible data assimilation library. Our TEC gradient observations are obtained from the Very Large Array Low-band Ionosphere and Transient Experiment (VLITE) and the TEC measurements are derived from GNSS receiver data. VLITE provides high precision and high spatial resolution TEC gradient observations over a small area, while GNSS observations supplement these with global coverage. By leveraging TEC observations in a physics-based model through data assimilation, we aim to improve our understanding of ionospheric processes and develop tools for improved ionospheric forecasting capabilities.

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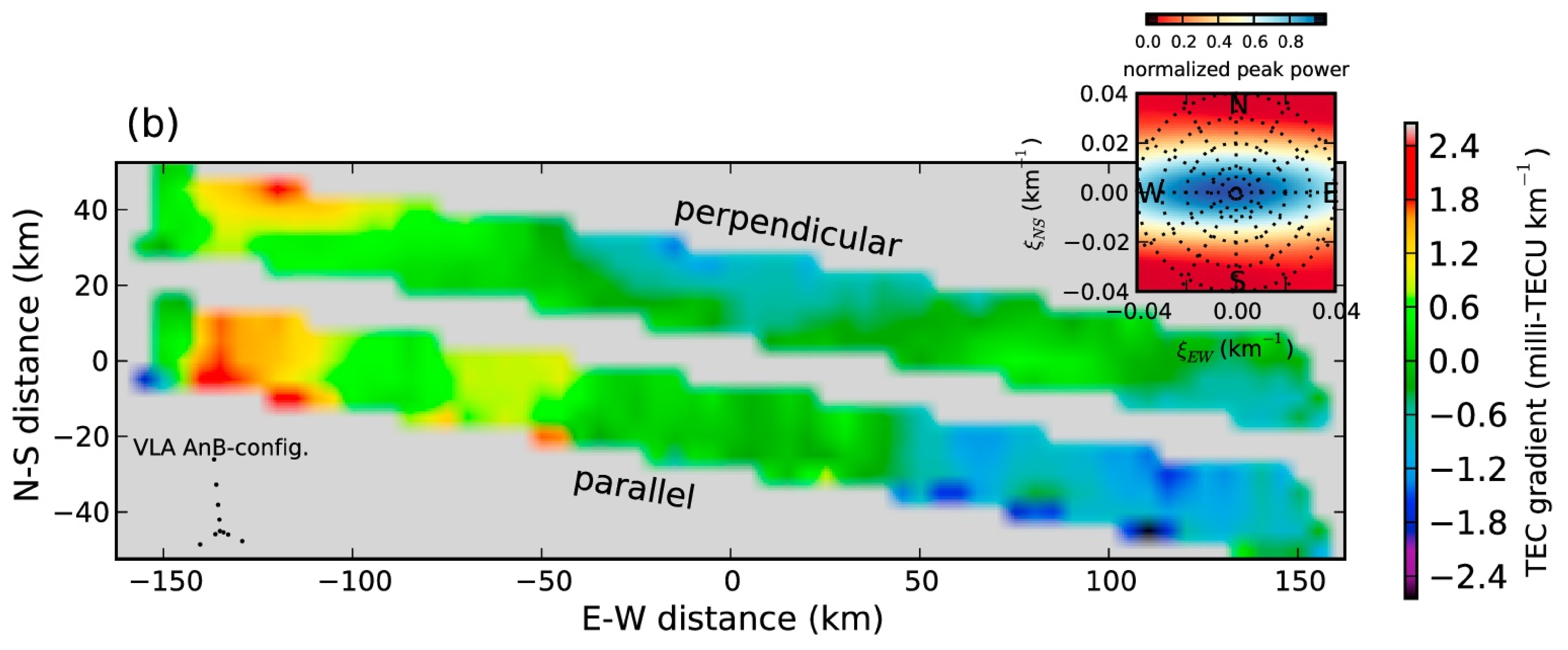
Background

Total electron content (TEC) observations can provide insights into electron density variations in the ionosphere. Such variations are associated with many aspects of ionospheric dynamics, including traveling ionospheric disturbances. In the present work we assimilate observations of TEC and horizontal TEC gradients into the SAMI3 (SAMI3 is Another Model of the Ionosphere 3D) ionosphere model. Assimilation into SAMI3 is accomplished using an ensemble Kalman filter implemented within LightDA, an extensible data assimilation library. Our TEC gradient observations are obtained from the Very Large Array Low-band Ionosphere and Transient Experiment (VLITE) and the TEC measurements are derived from GNSS receiver data. VLITE provides high precision and high spatial resolution TEC gradient observations over a small area, while GNSS observations supplement these with global coverage. By leveraging TEC observations in a physics-based model through data assimilation, we aim to improve our understanding of ionospheric processes and develop tools for improved ionospheric forecasting capabilities.

TEC observations

The NRL-developed VLA Low-band Ionosphere and Transient Experiment (VLITE, Helmboldt et al. 2019) provides a continuous stream of 320–384 MHz radio observations from the Very Large Array (VLA) radio telescope. This is used to compute differential TEC along the line of sight of the telescope, with a precision of about 0.01 TECU and a spatial resolution of kilometers, but with a field of view limited to tens of kilometers. World-wide GNSS TEC observations from the Madrigal database are used to supplement the VLITE observations.

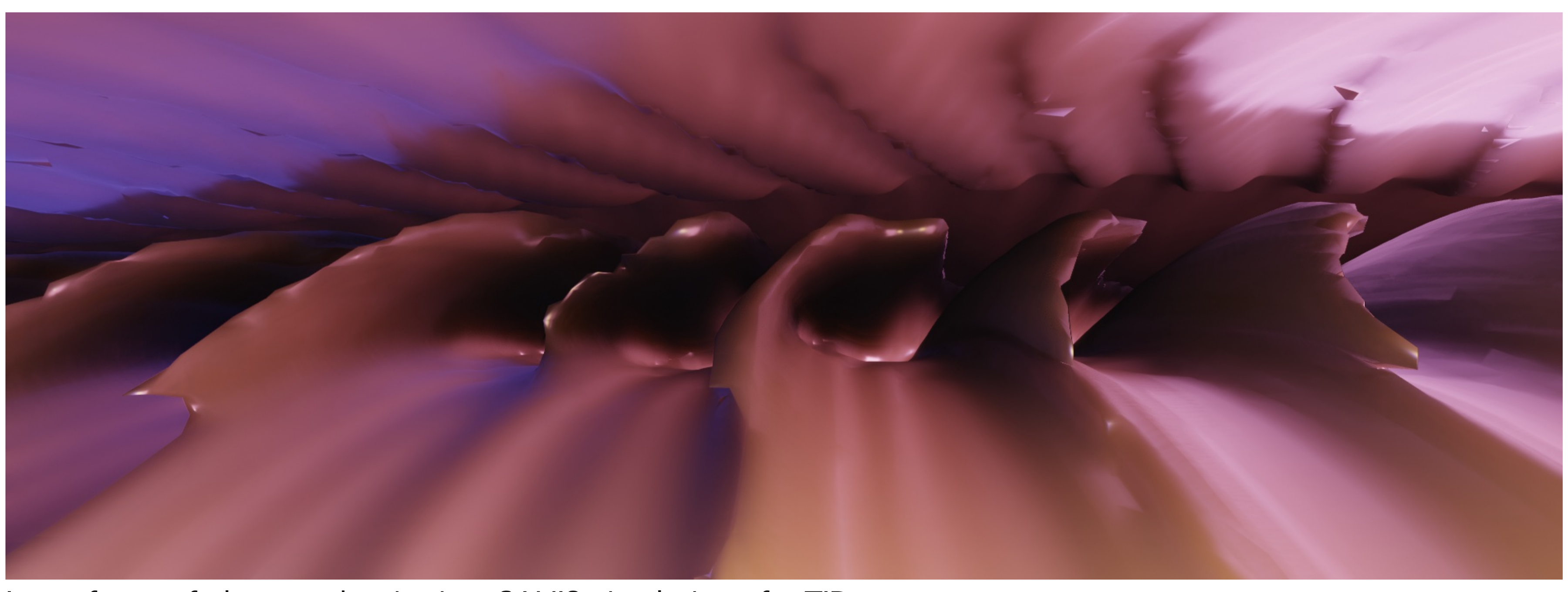


Helmboldt et al. 2014

Drift-scan image of differential TEC obtained using the VLA (Helmboldt et al. 2014).

SAMI3 model

Initial efforts to use LightDA on a real-world problem are focusing on assimilation of the SAMI3 ionosphere model (SAMI3 is Another Model of the Ionosphere 3D, Huba et al. 2000, Huba and Krall 2013). Previous work by Duly et al., 2014 has demonsrated that SAMI3's ability to model traveling ionospheric disturbances arising from idealized initial conditions; the present work aims to assimilatively model an observed TID using SAMI3.



Isosurfaces of electron density in a SAMI3 simulation of a TID.

TEC prediction

Assimilating TEC in SAMI3 requires computing TEC predictions from the SAMI3 state. This is accomplished by performing a line integral of the SAMI3 electron densities through the SAMI3 grid. An efficient algorithm has been developed that takes advantage of SAMI3's dipole grid, with a bisection search used to locate each integration point along its respective field line.

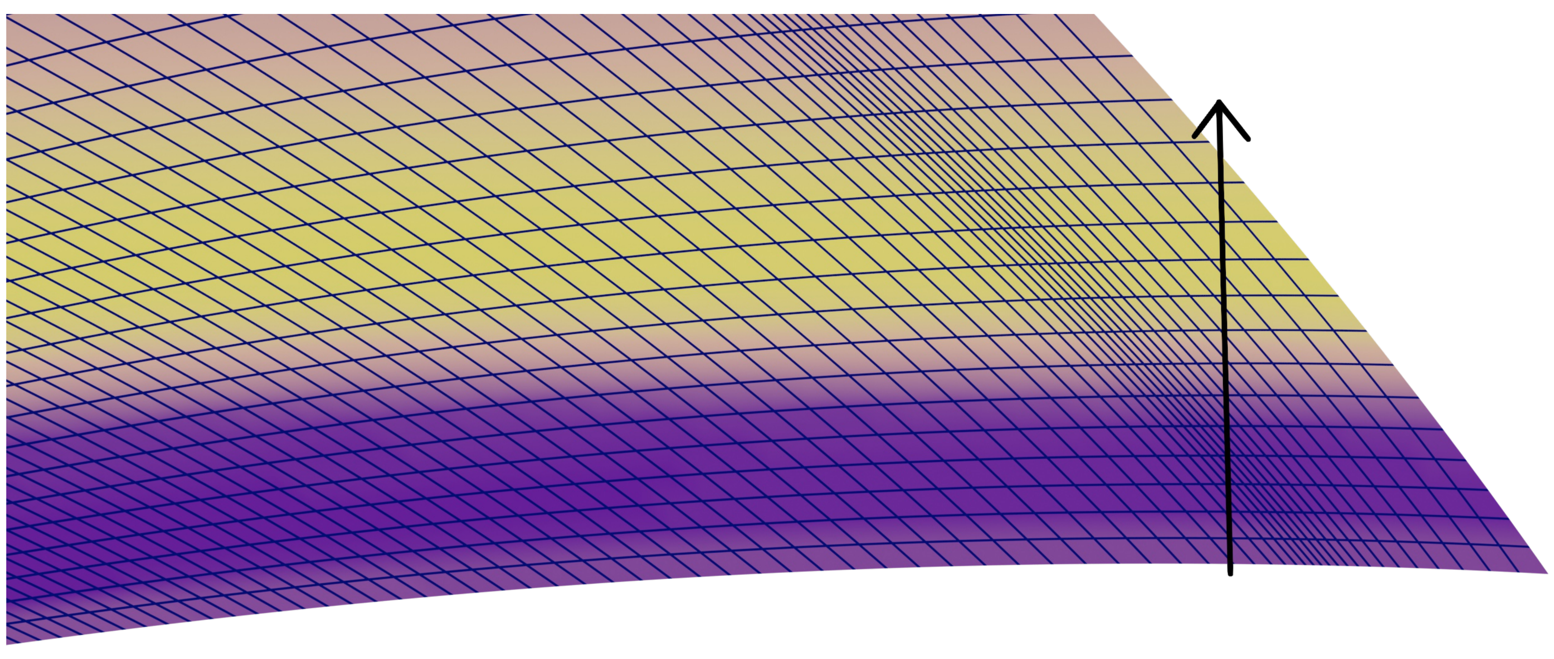


Illustration of the line integral performed through the SAMI3 grid for TEC prediction.

Data assimilation architecture

Data assimilation is accomplished using LightDA, a flexible data assimilation library designed for a supercomputing environment. LightDA provides extensible interfaces to work with different kinds of models and data assimilation algorithms. The model state array is automatically divided into sections to enable parallel assimilation. The filter implementation used in these tests is based on code from the Parallel Data Assimilation Framework (PDAF, Nerger 2005).

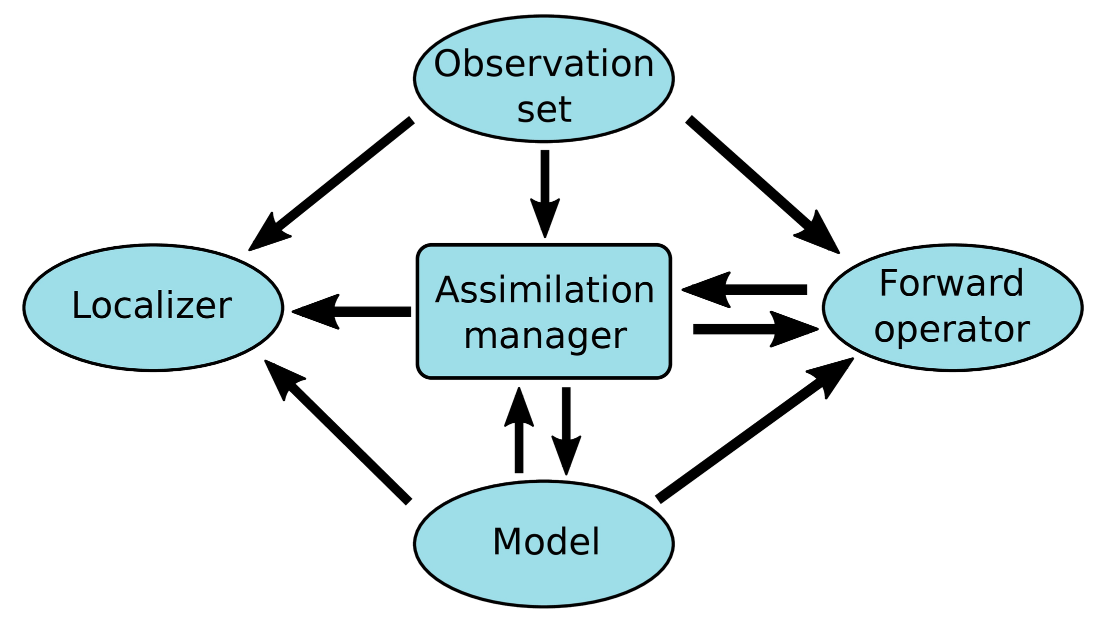


Diagram showing the key components of LightDA.

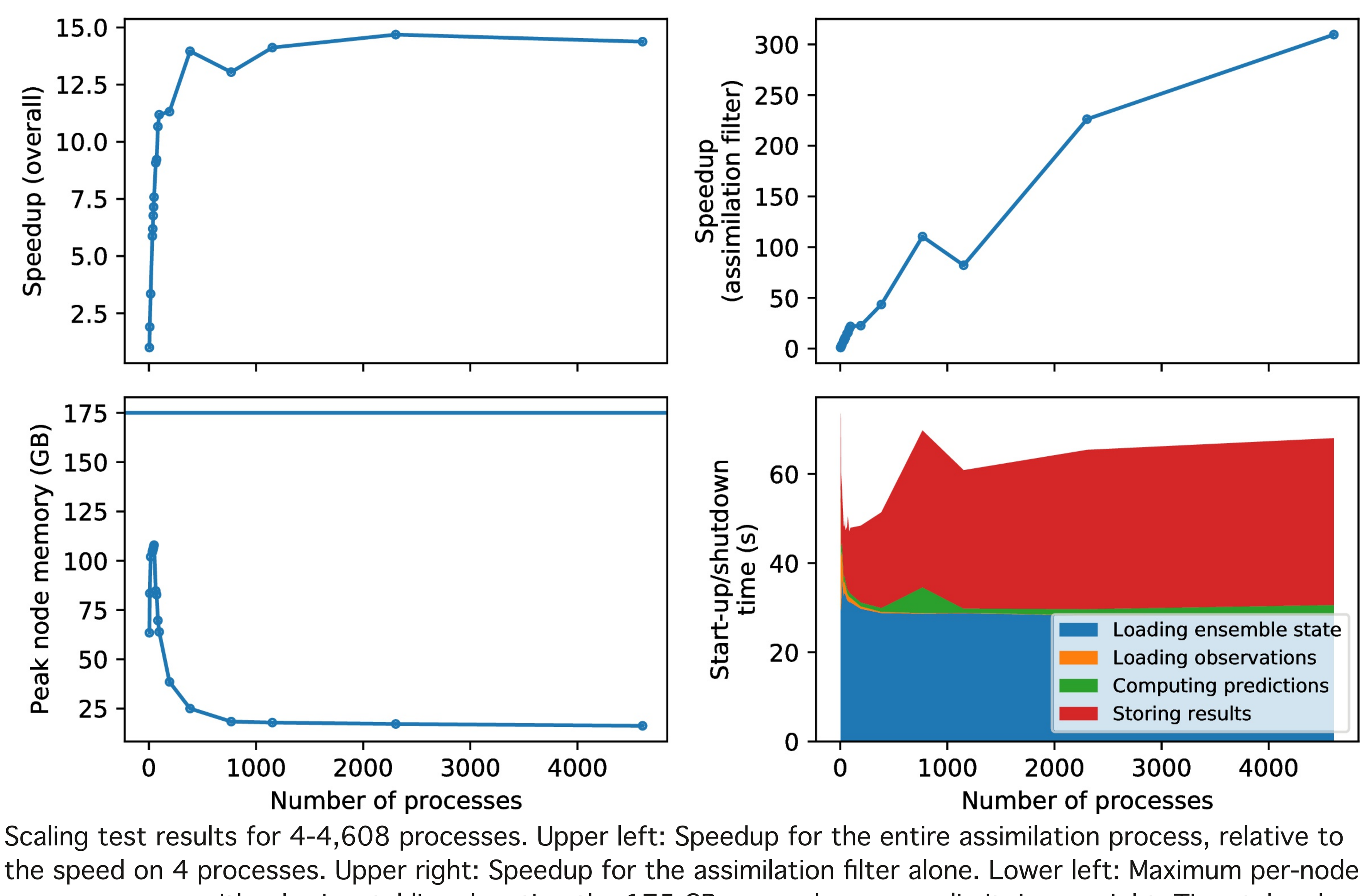
https://github.com/LightDA-assim/lightda-core

LightDA is open source (MIT license) and can be found on GitHub at the above link.

Parallel scaling tests

Scaling tests been conducted to over 4,600 MPI processes for assimilation of GNSS vertical TEC observations into SAMI3 using LightDA. The results demonstrate good parallelism in the assimilation filter. The start-up and shut-down tasks (mainly loading and saving the model state) are less scalable in the current implementation, accounting for the majority of the execution time beyond about 100 processes in this test.

Model state size	2.2 million
Number of ensemble members	15
Elements per batch	10,000



Scaling test results for 4-4,608 processes. Upper left: Speedup for the entire assimilation process, relative to the speed on 4 processes. Upper right: Speedup for the assimilation filter alone. Lower left: Maximum per-node memory usage, with a horizontal line denoting the 175 GB per-node memory limit. Lower right: Time taken by start-up and shut-down tasks.

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