Integration of 3D Earthquake Simulation & Real-Time Data Assimilation using h3-Open-BDEC

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- JSPS Grant-in-Aid for Scientific Research (S) (19H05662)
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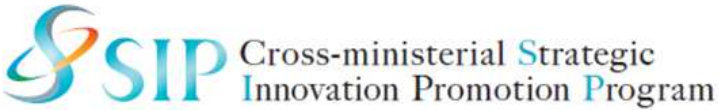
- Joint Usage/Research Center for Interdisciplinary Large-scale Information Infrastructures (JHPCN)
  - jh210022-MDH



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- **RIST**
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- **Nagoya University**
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National Institute for Environmental Studies

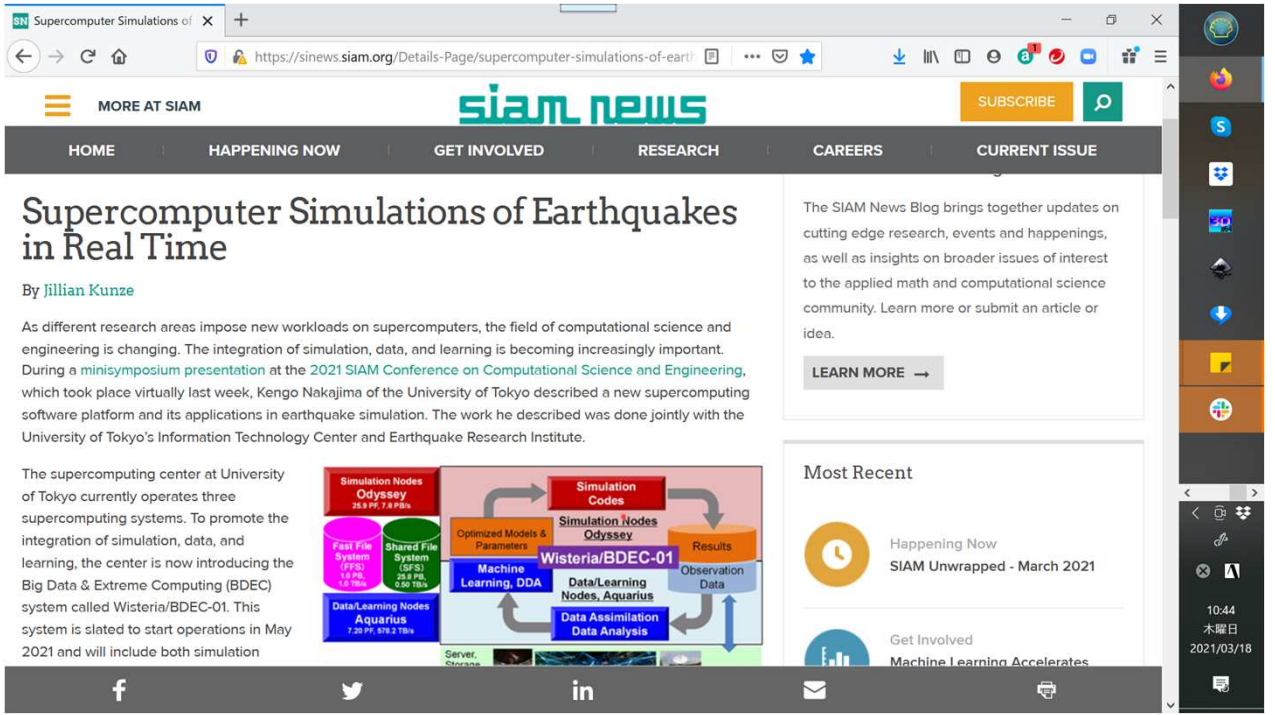
名古屋大学
NAGOYA UNIVERSITY

RIST

FUJITSU

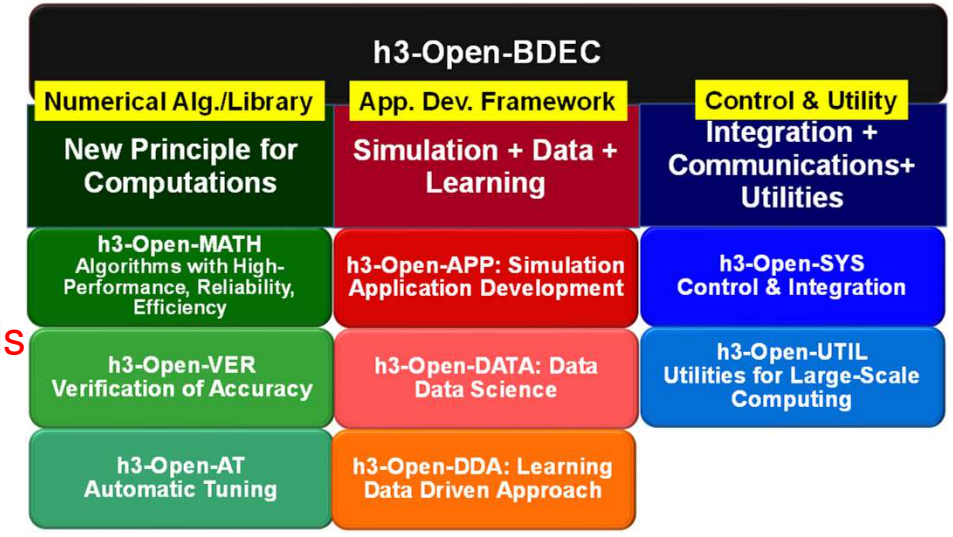
The article on my related presentation@SIAM CSE21 appeared in *SIAM News*

https://sinews.siam.org/Details-Page/supercomputer-simulations-of-earthquakes-in-real-time



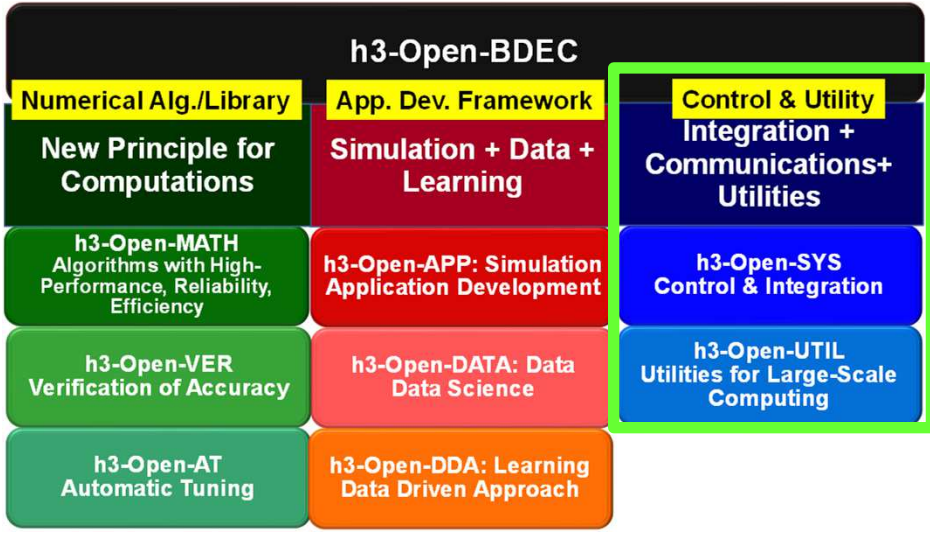
h3-Open-BDEC Innovative Software Platform for Integration of (S+D+L) on the BDEC System, such as Wisteria/BDEC-01

- Overview
  - 5-year project supported by Japanese Government (JSPS) since 2019
  - Leading-PI: Kengo Nakajima (The University of Tokyo)
  - Total Budget: 1.41M USD
- Two Innovations
  - New Principles for Numerical Analysis by Adaptive Precision, Automatic Tuning & Accuracy Verification
  - Hierarchical Data Driven Approach (*h*DDA) based on Machine Learning

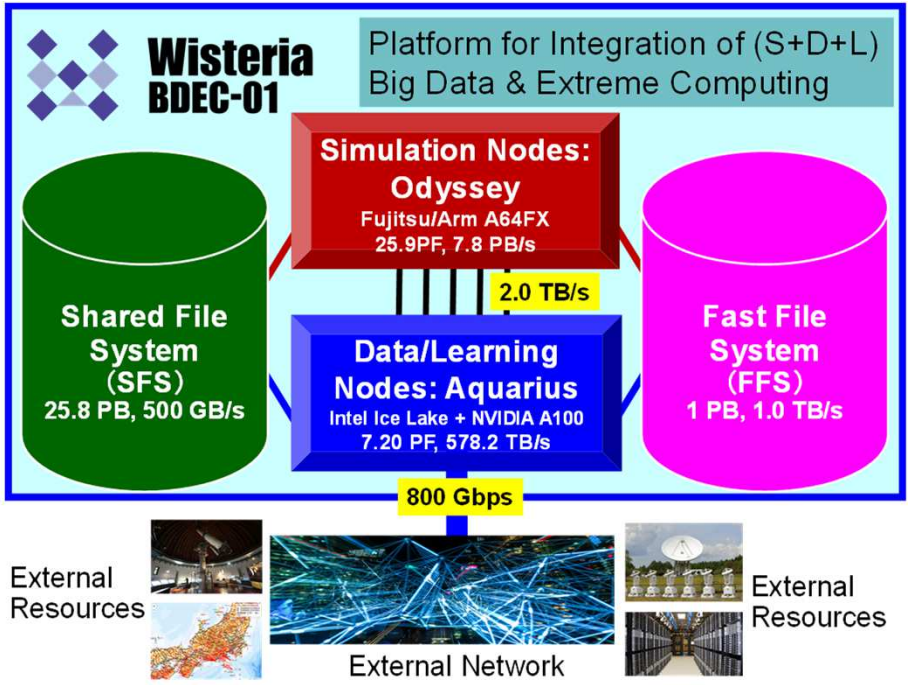


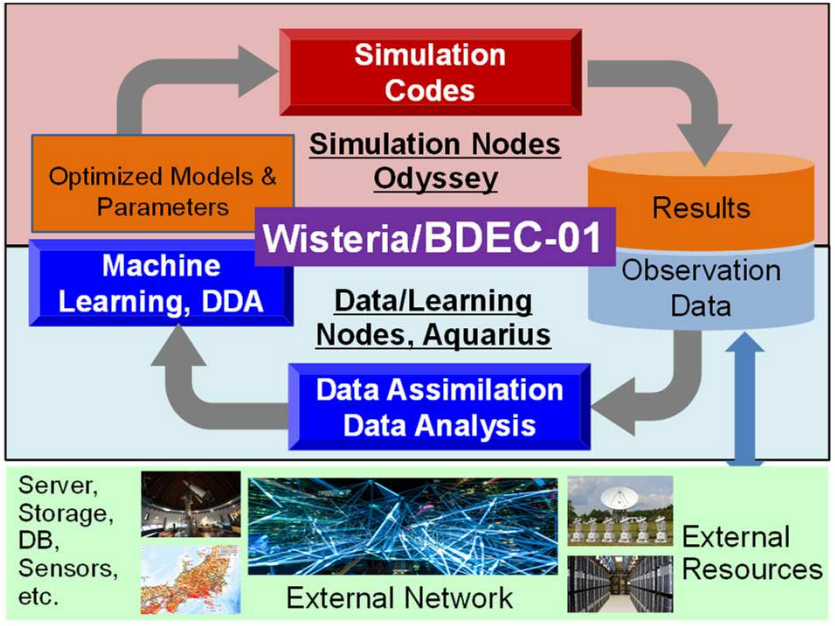
h3-Open-BDEC Innovative Software Platform for Integration of (S+D+L) on the BDEC System, such as Wisteria/BDEC-01

- "Three" Innovations
  - New Principles for Numerical Analysis by Adaptive Precision, Automatic Tuning & Accuracy Verification
  - Hierarchical Data Driven Approach (*h*DDA) based on Machine Learning
  - **Software & Utilities for Heterogenous Environment, such as Wisteria/BDEC-01**



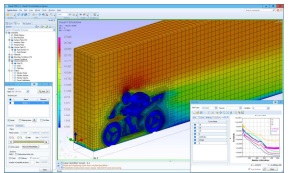
Wisteria/BDEC-01: The First "Really Heterogenous" System in the World

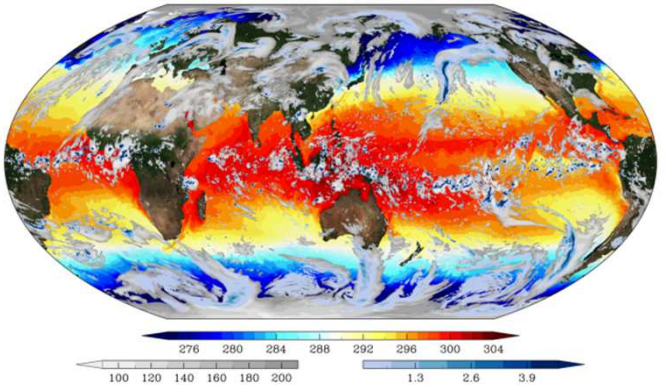


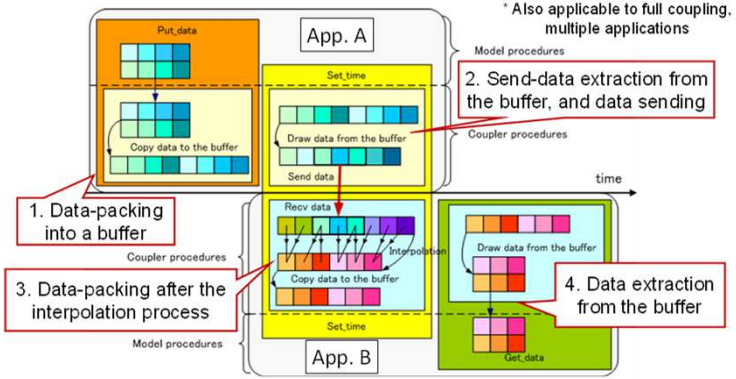


Possible Applications (S+D+L) on Wisteria/BDEC-01 with h3-Open-BDEC

- Simulations with Data Assimilation
  - Very Typical Example of (S+D+L)
- Atmosphere-Ocean Coupling for Weather and Climate Simulations
  - AORI/U.Tokyo, RIKEN R-CCS, NIES
- **Earthquake Simulations with Real-Time Data Assimilation**
  - **ERI/U. Tokyo**
- Real-Time Disaster Simulations
  - Flood, Tsunami
- (S+D+L) for Existing Simulation Codes (Open Source Software)
  - OpenFOAM







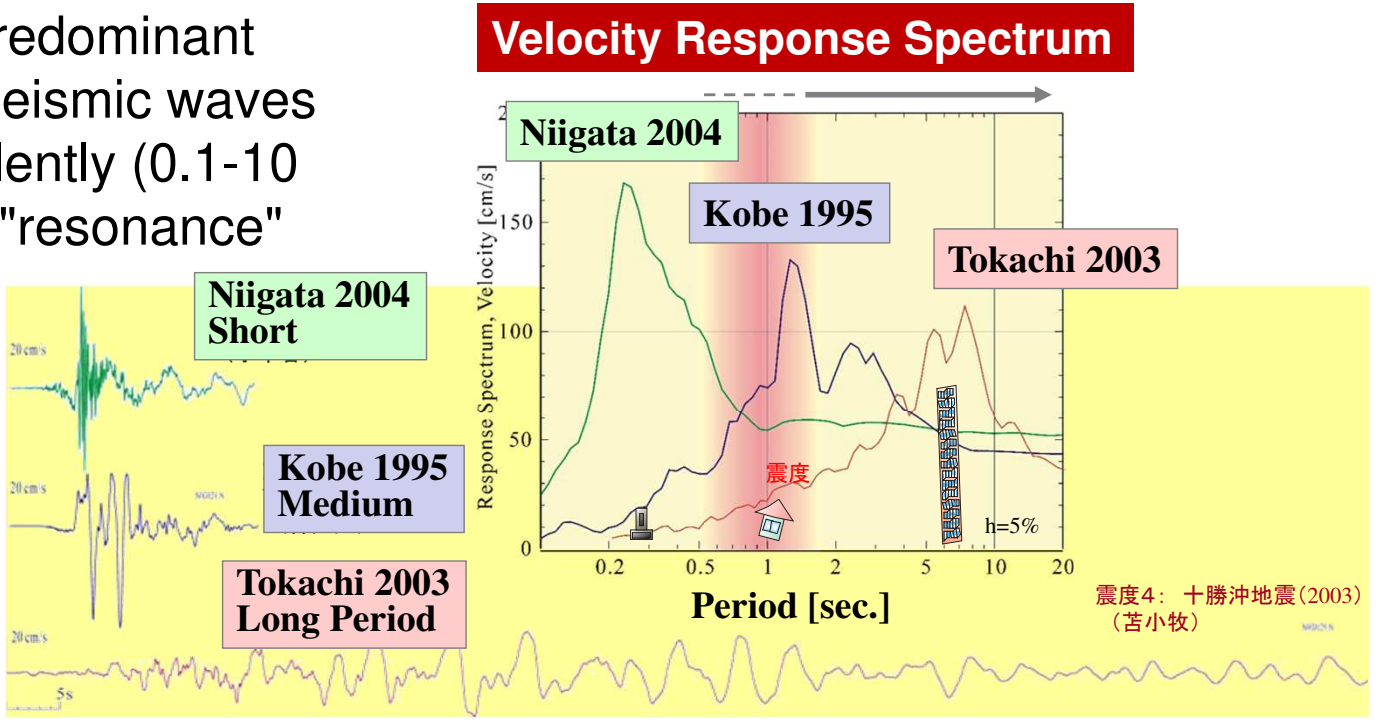
- **Earthquake Simulation/Real-Time Data Assimilation**
  - **Seism3D/OpenSWPC-DAF by Prof. Furumura (ERI/U.Tokyo)**
  - **Preliminary Works on OBCX**
- The 3rd Pillar of h3-Open-BDEC
  - H3-Open-UTIL/MP
  - h3-Open-SYS/WaitIO
- Summary

Early Forecast of Long-Period Ground Motions via Data Assimilation of Observation and Simulations [Furumura et al. 2019]

- New method for the early forecast of long-period (> 3–10 s) ground motions generated by large earthquakes based on the data assimilation of observed ground motions and FDM simulations of seismic wave propagation in a 3-D heterogeneous structure (**Seism3D/OpenSWPC-DAF**(**Data-Assimilation-Based Forecast**)).
- **This approach uses the dense nationwide network in Japan and supercomputers to perform forecasts using the assimilated wavefields at speeds much faster than the actual wave propagation speed.**
- **An early alert can be issued prior to the occurrence of strong motions due to large, distant earthquakes.**
- Validation of the effectiveness of this data-assimilation-based forecast approach via numerical tests for the early forecast of long-period ground motions in central Tokyo using the observed waveform data from the Mw6.6 2007 Off Niigata and Mw9.0 2011 Off Tohoku earthquakes.

Seismic Wave: Various Components of Wavelength

- Buildings with the same natural period as the predominant component of seismic waves shake most violently (0.1-10 sec.): a kind of "resonance"
- **Long-period waves last long and reach far**



[c/o Prof. T. Furumura, ERI/U.Tokyo]

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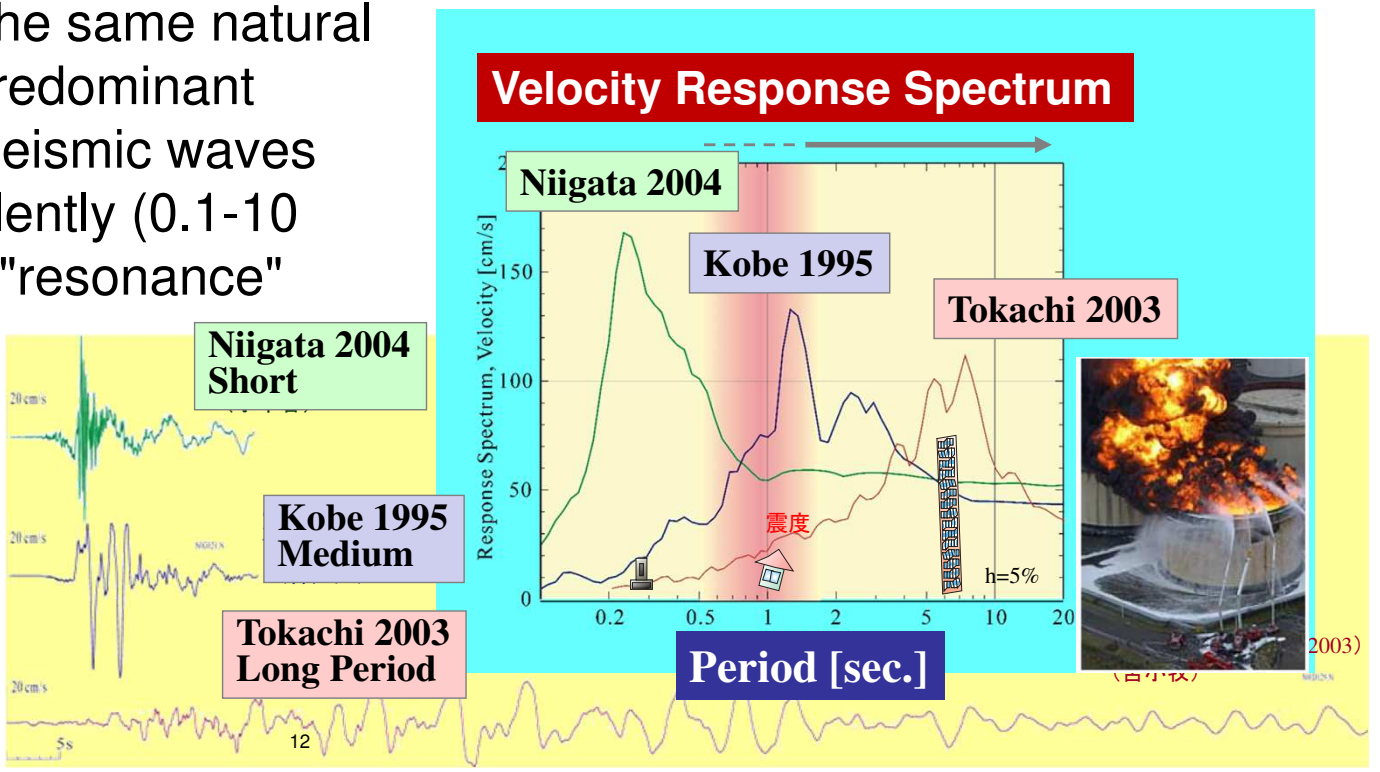
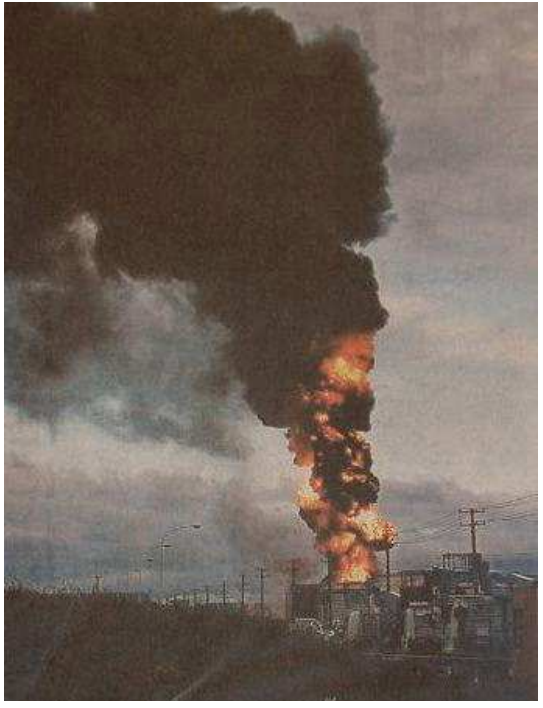
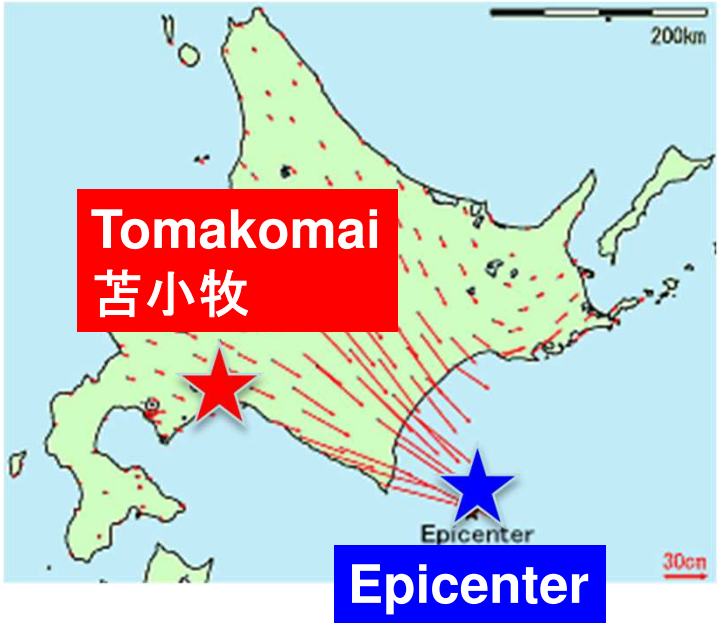


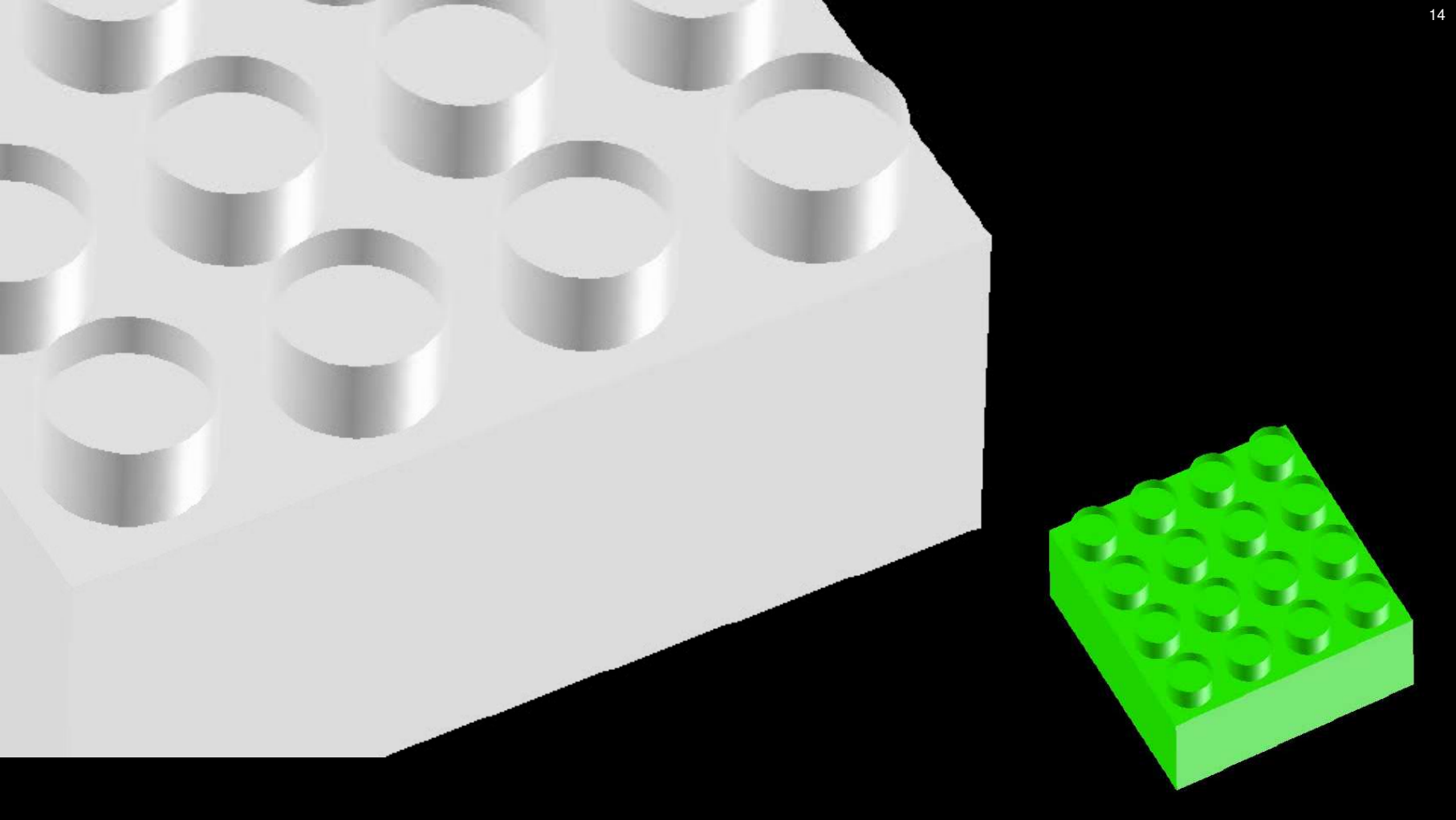
[c/o Prof. T. Furumura, ERI/U.Tokyo]

2003 Tokachi Earthquake: Long-Period

Big Fire Accident of Oil Tanks in City of Tomakomai (200+km from Epicenter) due to Sloshing

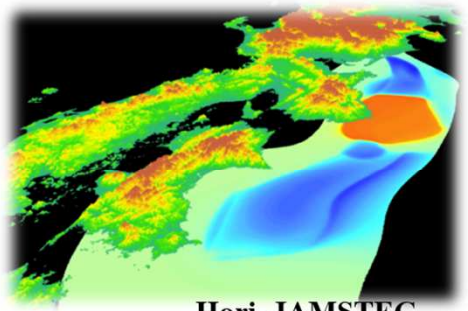






Task of simulation: understanding earthquake dynamics

(a) Earthquake source model



Hori, JAMSTEC

(b) Subsurface structural model

Forward modeling

Inversion

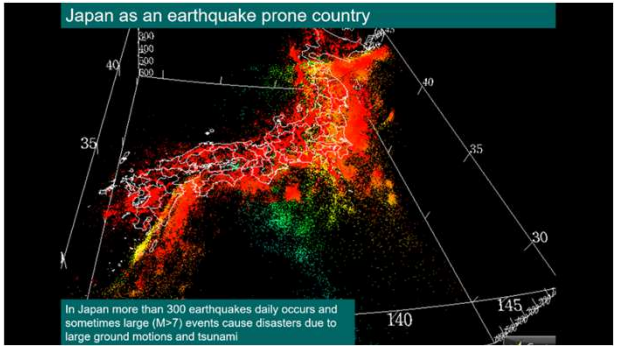
(c) Earthquake (seismic) ground motion simulation

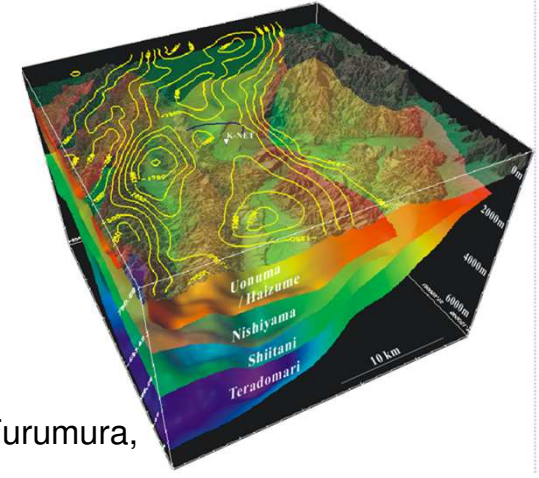
[c/o Prof. T. Furumura, ERI/U.Tokyo]

To understand the past earthquake and for mitigate disasters for future events computer simulation of ground motion is employed with source and subsurface structural models

Earthquake simulation is always with uncertainty

- Subsurface/Underground Structure
  - Heterogenous, Random, Stochastic
  - Fluctuations
- **Integration of Simulation/Observation is essential**
- Traditional Simulations
  - Forward Simulations
- **New Types of Methods for Simulations combined with Data Assimilation/Real-Time Observation is under development**
  - **Forecast by Simulations, Correction by Data Assimilation**



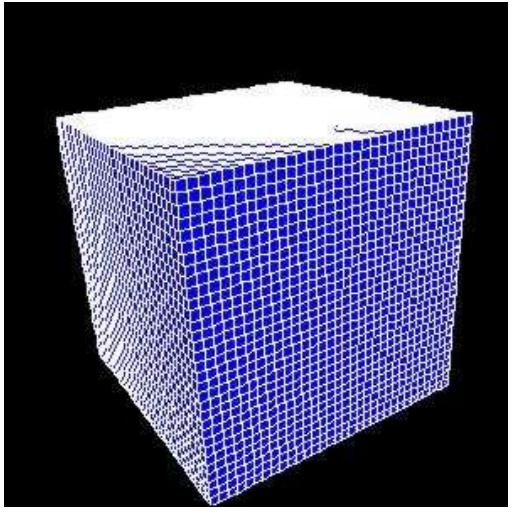


[c/o Prof. T. Furumura, ERI/U.Tokyo]

Simulations of Long-Period Ground Motion [Furumura et al.]

- 3D Equation of Motions solved by FDM (Finite-Difference Method)

$$v_p^n = v_p^{n-1} + \frac{1}{\rho}\left(\frac{\partial \sigma_{xp}^{n-1/2}}{\partial x} + \frac{\partial \sigma_{yp}^{n-1/2}}{\partial y} + \frac{\partial \sigma_{zp}^{n-1/2}}{\partial z} \right) \Delta t \quad (p = x, y, z)$$

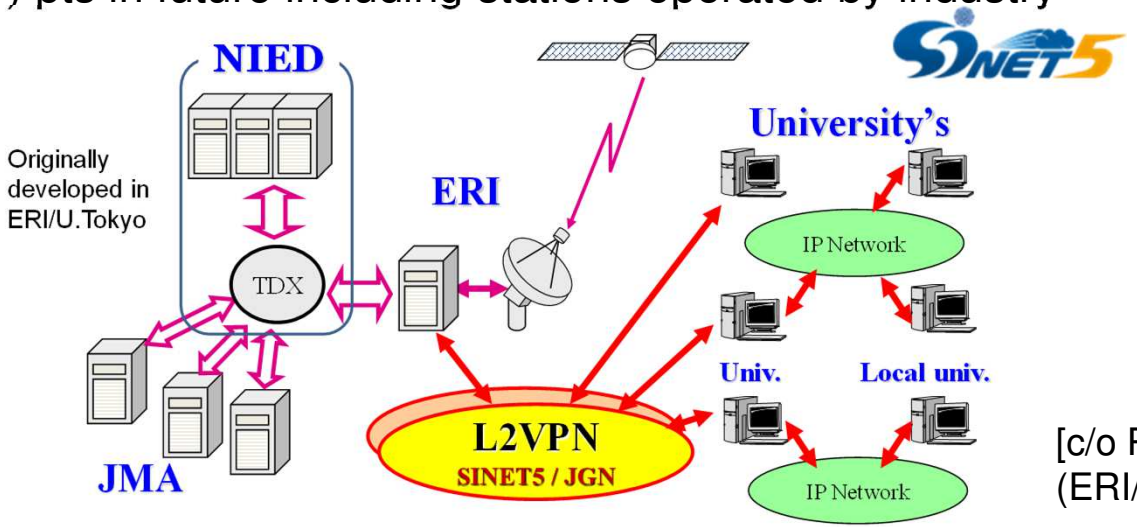


- Seism3D
  - Staggered Discretization in Space/Time
  - 4th order in Space
  - 2nd order in Time (Explicit Time Marching)
  - OpenMP + MPI, Fortran

Real-Time Sharing of Seismic Observation is possible in Japan by JDXnet with SINET

Japan Data eXchange network

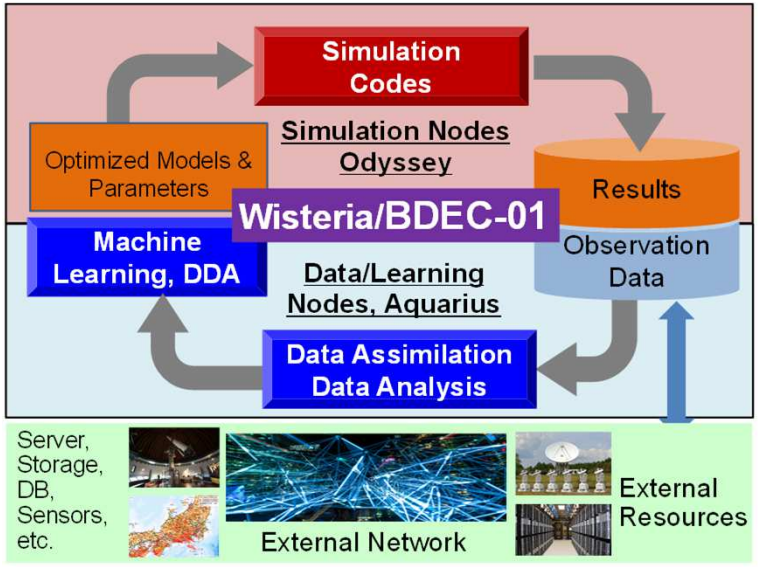
- Seismic Observation Data (100Hz/3-dir's/O(10^3) observation points) by JDXnet is available through SINET in Real Time
  - O(10^2) GB/day: available at Website of NIED
  - O(10^5) pts in future including stations operated by industry

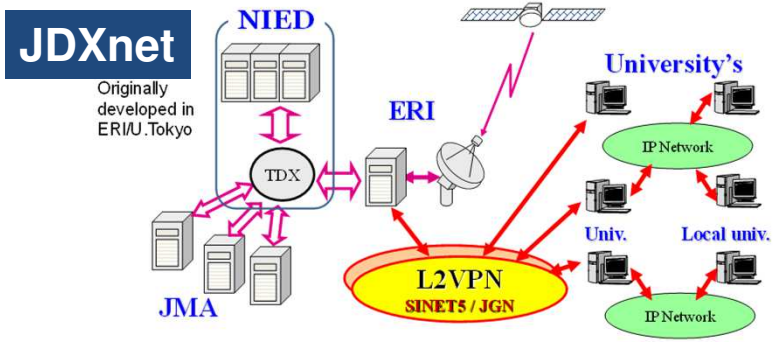


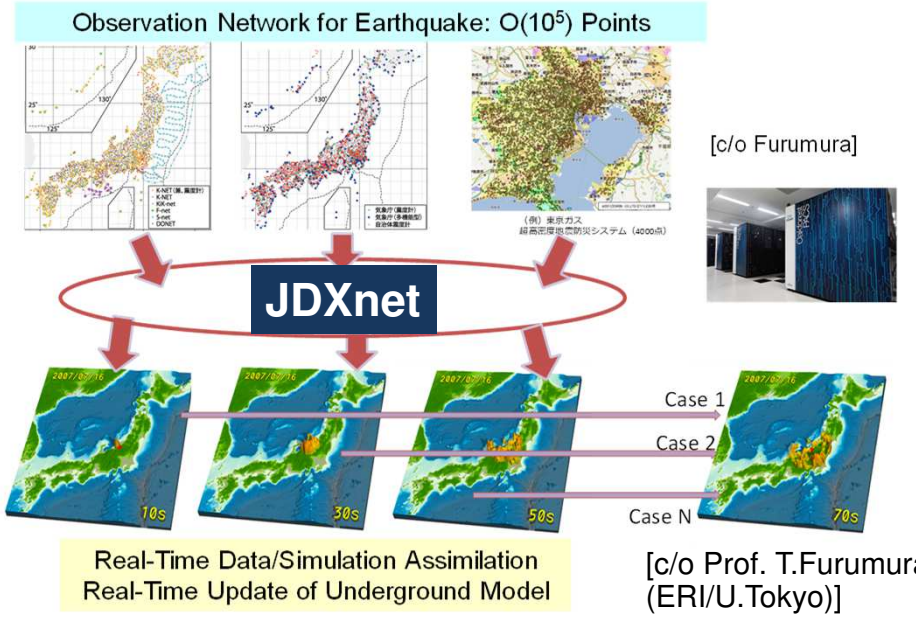
[c/o Prof. H.Tsuruoka (ERI/U.Tokyo)]

3D Earthquake Simulation with Real-Time Data Observation/Assimilation

Simulation of Strong Motion (Wave Propagation) by 3D FDM







[c/o Prof. T.Furumura (ERI/U.Tokyo)]

Real-Time Assimilation of "Observation+Computation" in Seismic Wave Propagation [c/o Oba & Furumura]

- **Data Assimilation of Wave Propagation by "Optimal Interpolation Technique"**

Assim. Comp. Residual Obs. Comp.

$$x_n^a = x_n^f + W(y_n - Hx_n^f)$$

Comp. Assim.

$$x_{n+1}^f = Fx_n^a$$

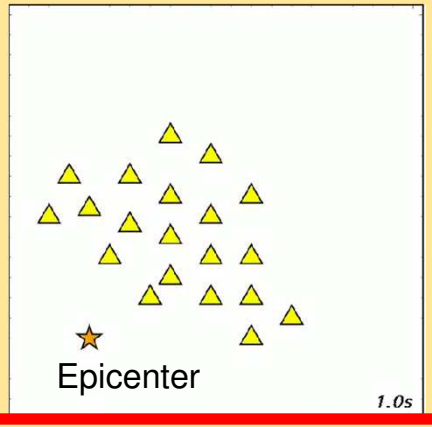
n: Time Step

W: **Weighting Matrix**

F: Wave Propagation simulation

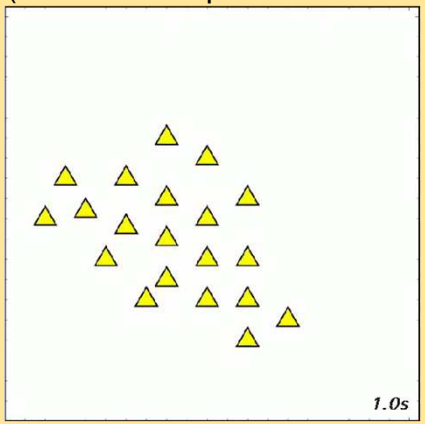
(A) Pure Simulation

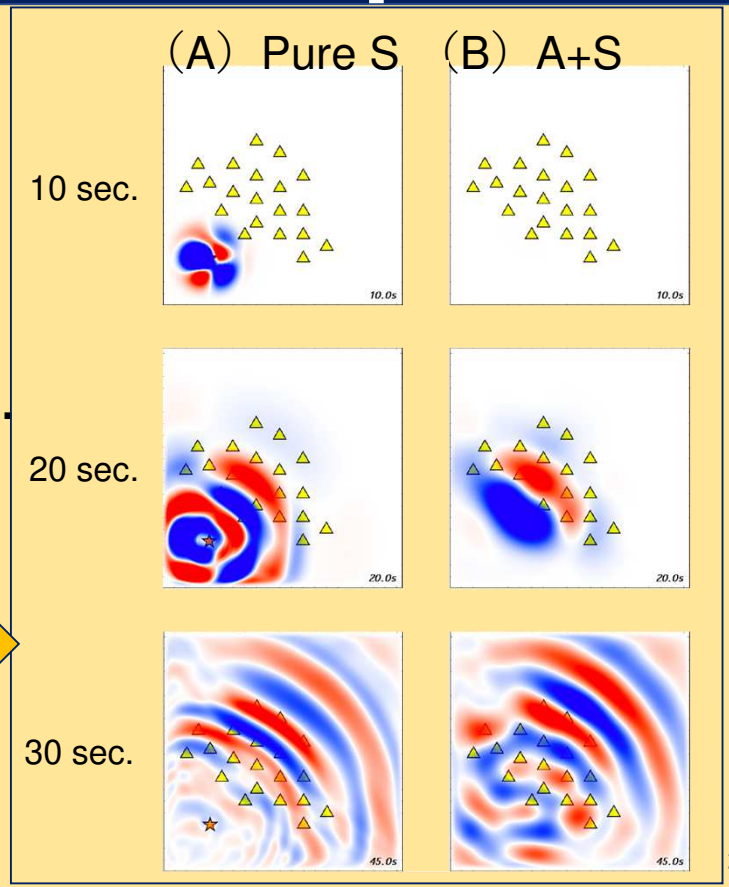
△: Obs. Pts.



(B) Assimilation+Sim.

(No info for Epicenter needed)





Real-Time Assimilation of "Observation+Computation" in Seismic Wave Propagation [c/o Oba & Furumura]

- **Data Assimilation of Wave Propagation by "Optimal Interpolation Technique"**

Residual

Assim. Comp. Obs. Comp.

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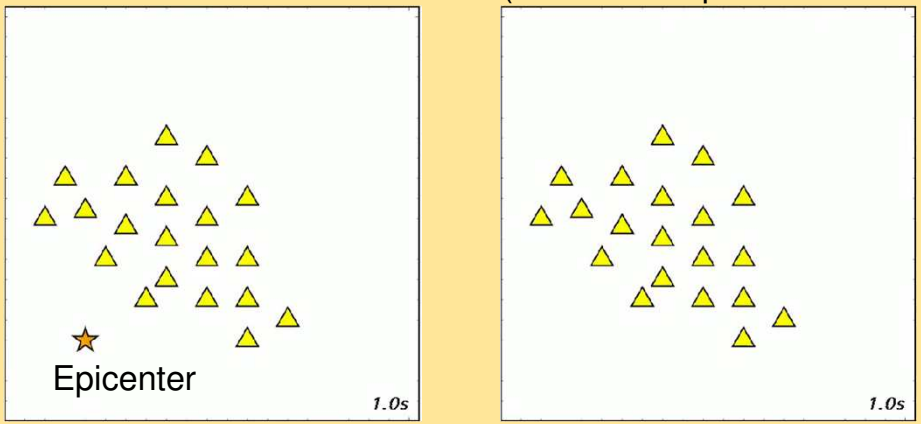
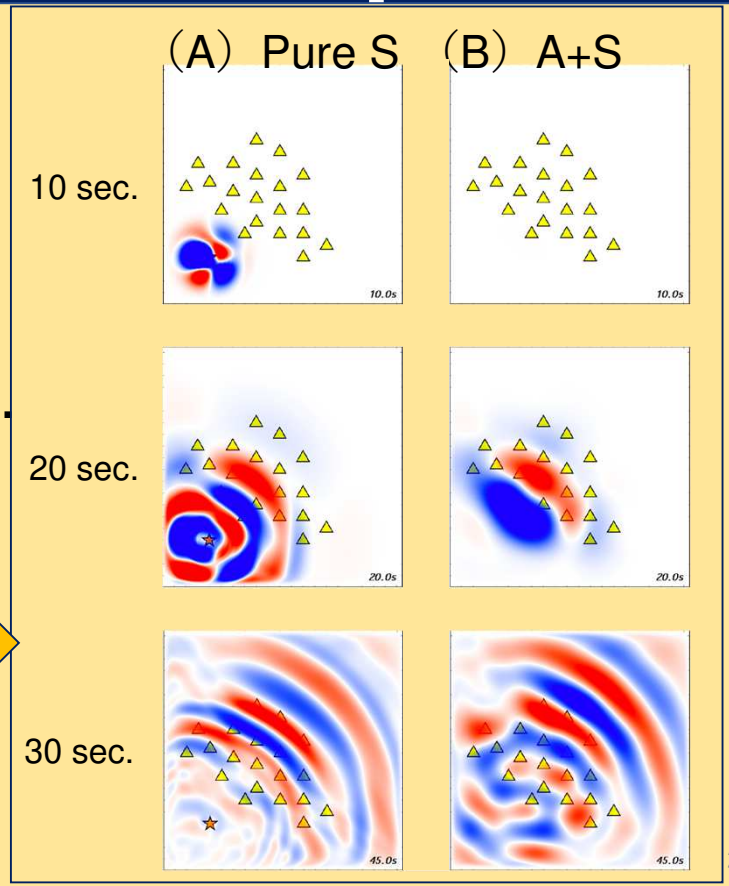
(A) Pure Simulation **(B) Assimilation+Sim.**

△: Obs. Pts. (No info for Epicenter needed)





Starting from (A+S: Assim+Sim.) to (Pure S: Pure Simulation)

Residual

Assim. Comp. Obs. Comp.

$$x_n^a = x_n^f + W(y_n - Hx_n^f)$$

$$x_{n+1}^f = Fx_n^a$$

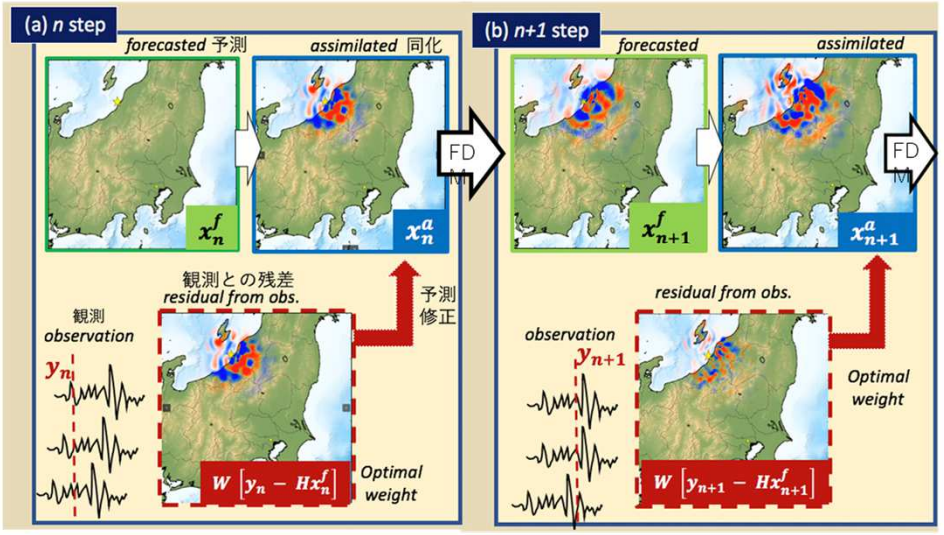
Comp. Assim.

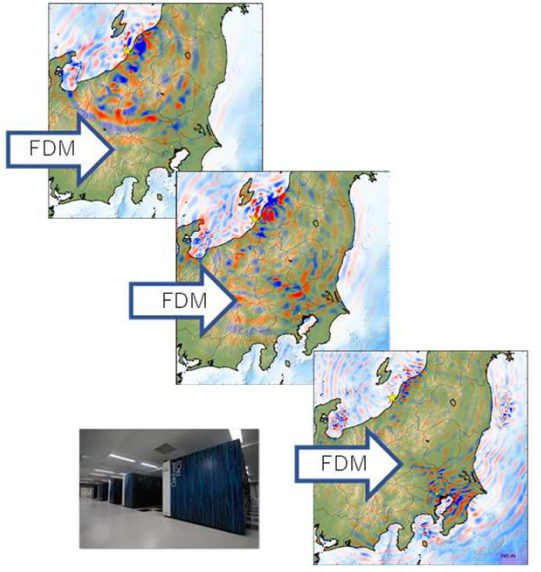
n: Time Step

W: **Weighting Matrix**

F: Wave Propagation simulation

(A+S) Assimilation+Simulation → **(Pure S) Pure Simulation/Forecast**





[c/o Prof. T. Furumura, ERI/U.Tokyo]

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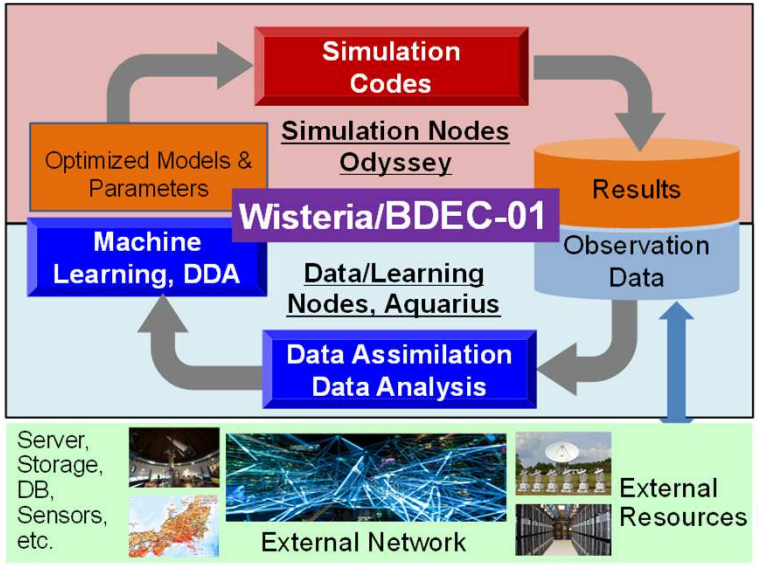
  - **Preliminary Works on OBCX**
- The 3rd Pillar of h3-Open-BDEC
  - H3-Open-UTIL/MP
  - h3-Open-SYS/WaitIO
- Summary

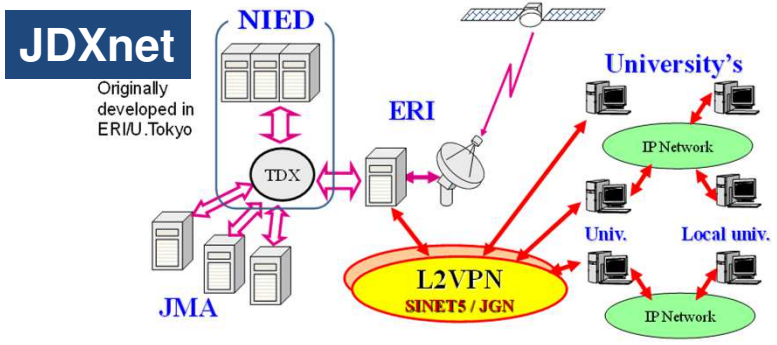
Goal of the Present Work

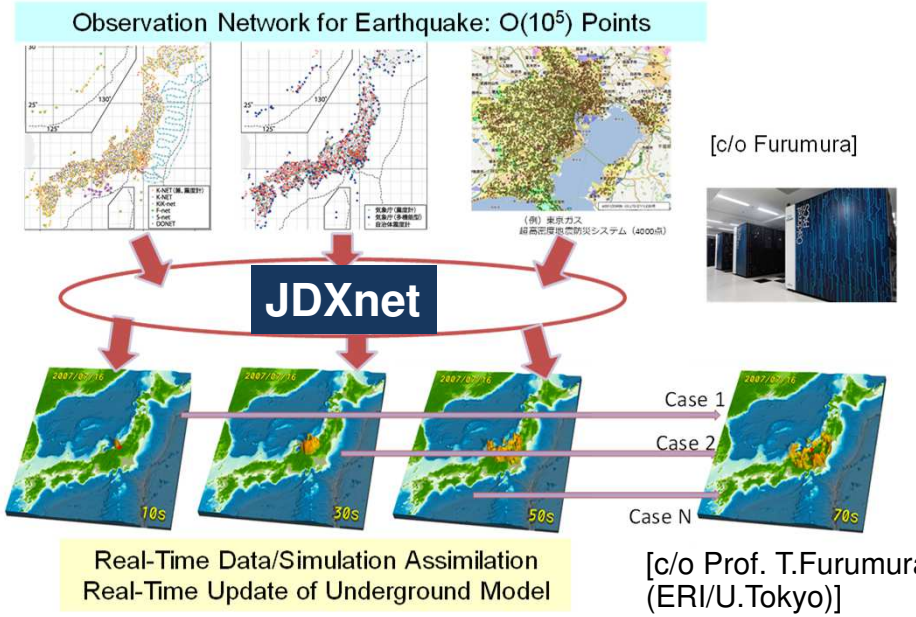
- Seism3D/OpenSWPC-DAF
  - 3D Simulations by FDM
  - Data Assimilation of Observed Ground Motions
- Observed data sets were downloaded from NIED's webpage
  - Not a "really" real-time
- Goal of the present work is development of a framework for real time combination of simulation-assimilation for long-period ground motions

3D Earthquake Simulation with Real-Time Data Observation/Assimilation

Simulation of Strong Motion (Wave Propagation) by 3D FDM



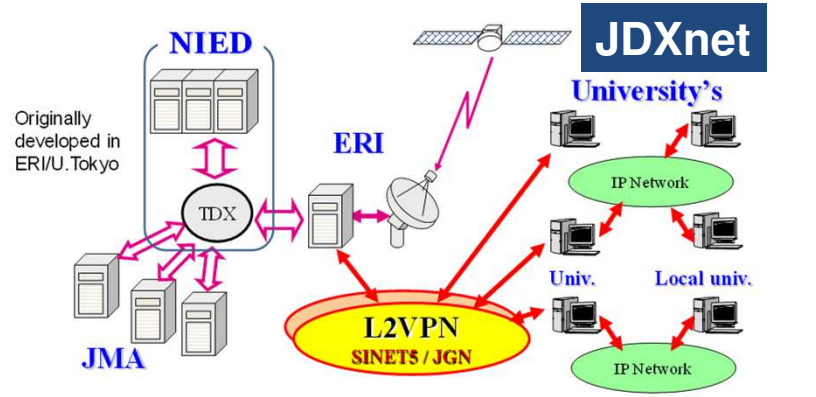


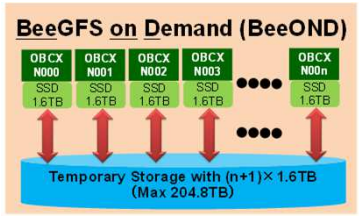


[c/o Prof. T.Furumura (ERI/U.Tokyo)]

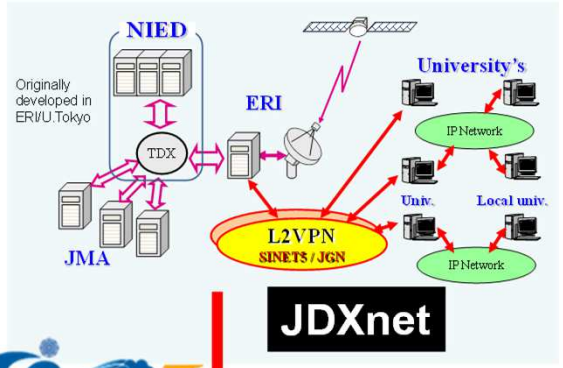
Preliminary Works on Oakbridge-CX (OBCX)

- Intel Xeon Platinum 8280 (Cascade Lake, CLX), Fujitsu
  - 1,368 nodes, 6.61 PF peak, 385.1 TB/sec, 4.2+ PF for HPL **#110 in 58th Top500 (Nov.2021)**
  - Fast Cache: SSD's for 128 nodes: Intel SSD, BeeGFS: 200+TB Fast FS
    - 1.6 TB/node, 3.20/1.32 GB/s/node for R/W
    - 16 of these nodes can directly access external resources (server, storage, sensor network etc.) through SINET
- Switching to Wisteria/BDEC-01 after May 2021





16 of 128 nodes with SSD can access external resources directly through SINET (**External Nodes**)



3D Simulation + Real-Time Data Assimilation on OBCX

Seism3D/OpenSWPC-DAF: 3D FDM (Finite-Difference Method)

SINET5

Filter

An External Node of OBCX

Normal Condition

Initial Velocity Distribution by Interpolation for Seism3D/OpenSWPC-DAF using $O(10^1)$ nodes

Initial Velocity Field

Emergency Condition

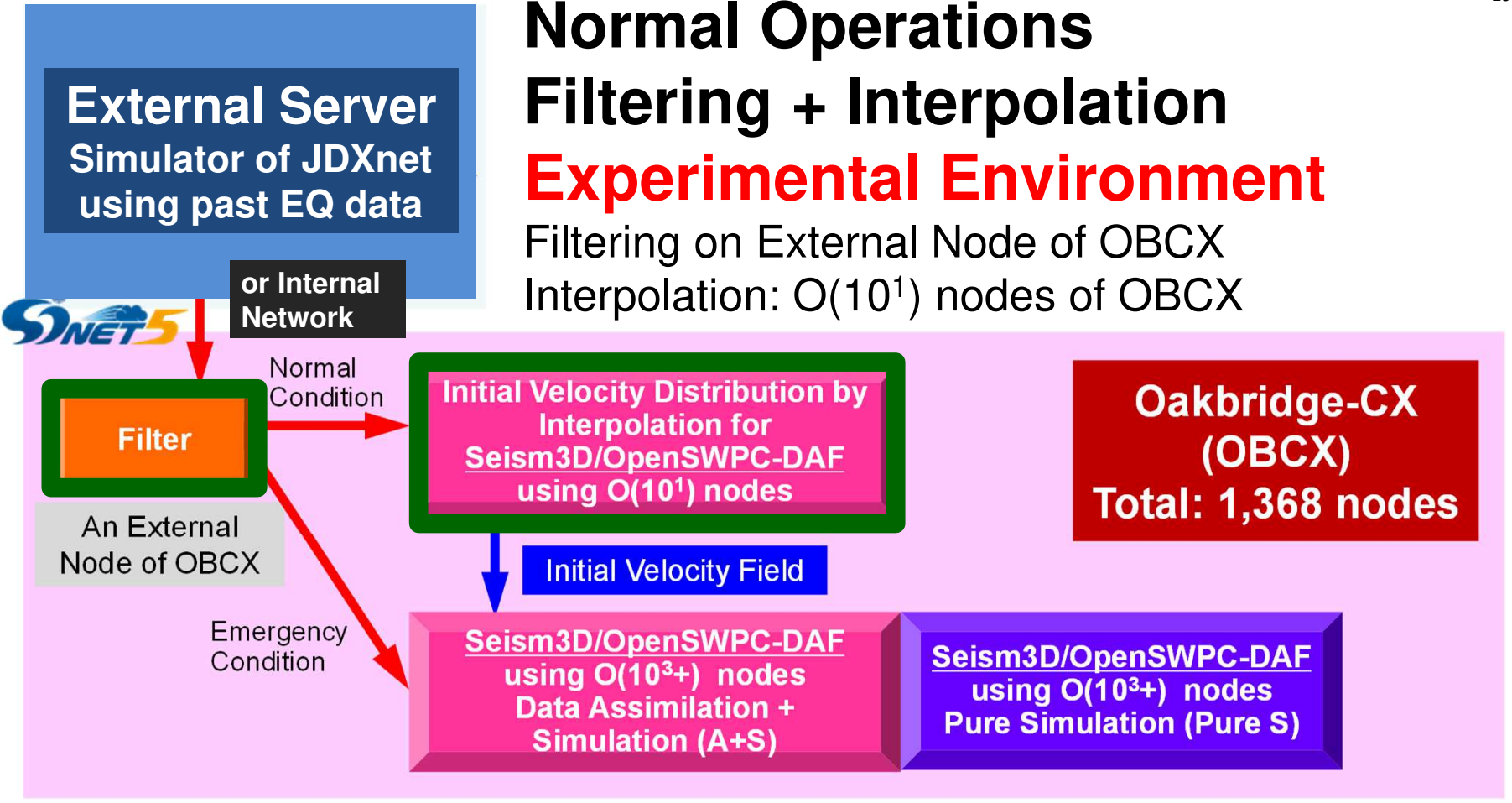
Seism3D/OpenSWPC-DAF using $O(10^3+)$ nodes Data Assimilation + Simulation (A+S)

Seism3D/OpenSWPC-DAF using $O(10^3+)$ nodes Pure Simulation (Pure S)

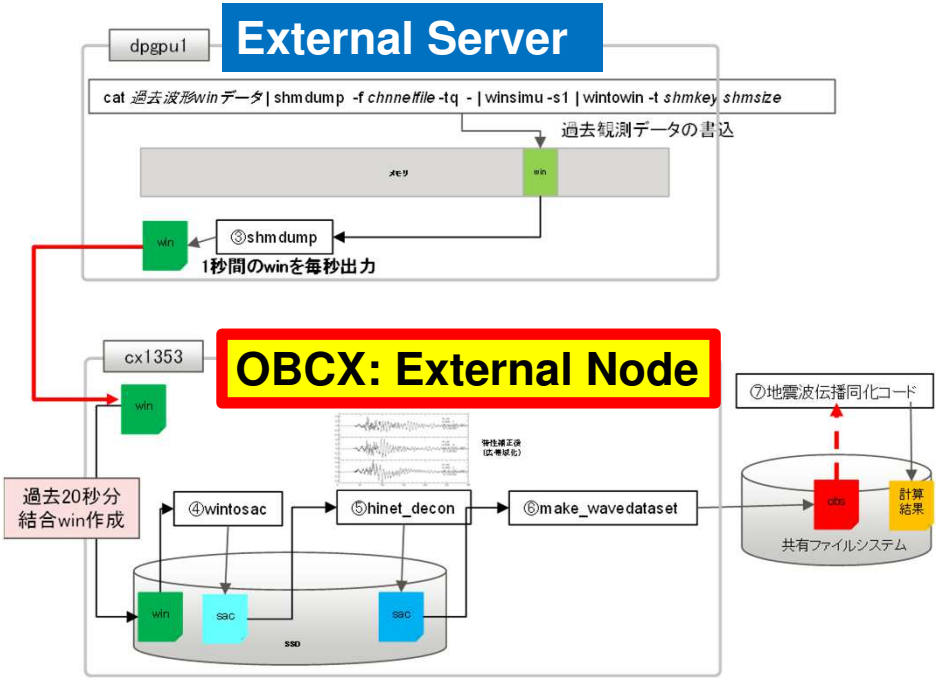
Oakbridge-CX (OBCX) Total: 1,368 nodes

Normal Operations
Filtering + Interpolation
Experimental Environment

Filtering on External Node of OBCX
Interpolation: O(10^1) nodes of OBCX

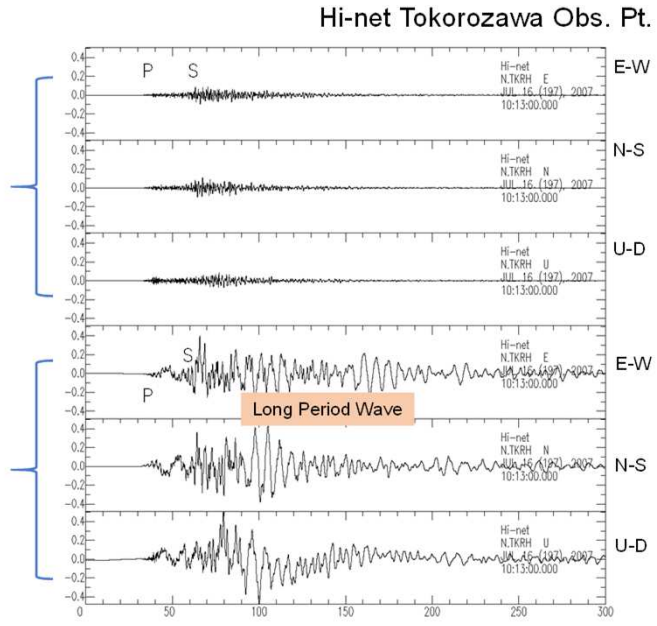


Filtering using Experimental Environment



(Before)
Only Short
Period

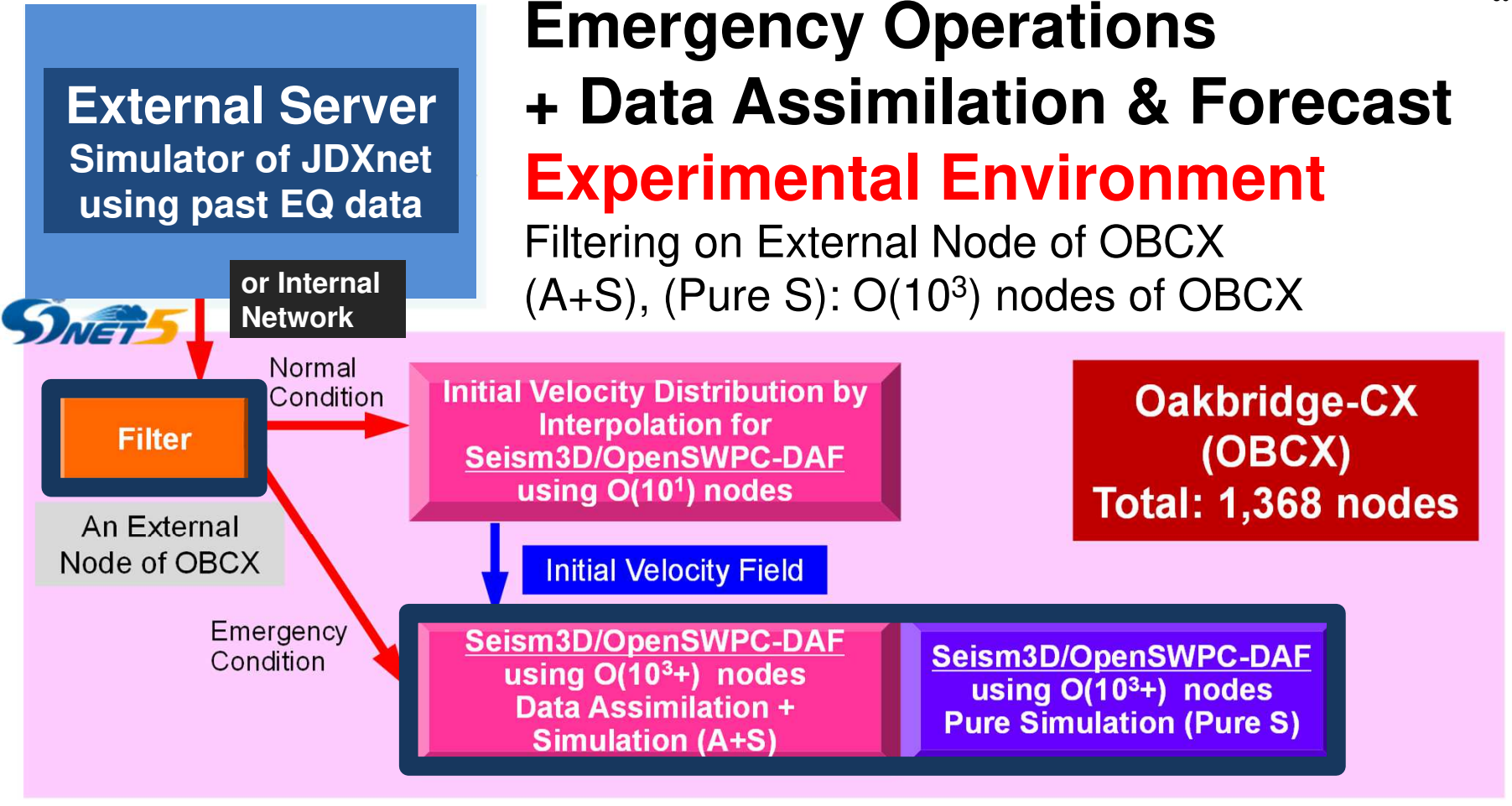
(After)
Effects of
Broadband
considered



Emergency Operations + Data Assimilation & Forecast

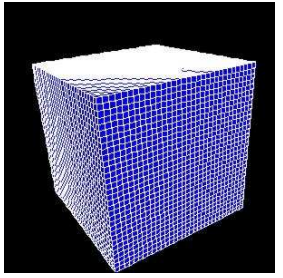
Experimental Environment

Filtering on External Node of OBCX
(A+S), (Pure S): O(10^3) nodes of OBCX



Example: Off Niigata 2007 Mw6.6 Earthquake

- Observed Data: Stored in External Server (Mini-mdx)
- An external node of OBCX receives observed data, and apply filtering
- “Data Assimilation + Simulation (A+S)”, and “Forecast by Simulation (Pure S)” are separated codes, while same number of computing nodes were used
- Movies were created after simulations (O(10) sec.)



- Seism3D/OpenSWPC-DAF
  - 3D FDM + Optimal Interpolation Technique for Data Assimilation
  - Each Mesh: 240m × 240m × 240m
  - 1,920 × 1,920 × 240 meshes (8.85×10^8)
  - 460.8 km × 460.8 km × 57.6 km

$$v_p^n = v_p^{n-1} + \frac{1}{\rho}\left(\frac{\partial \sigma_{xp}^{n-1/2}}{\partial x} + \frac{\partial \sigma_{yp}^{n-1/2}}{\partial y} + \frac{\partial \sigma_{zp}^{n-1/2}}{\partial z}\right)\Delta t \quad (p = x, y, z)$$

n: Time Step

Residual

Assim. Comp. Obs. Comp.

$$\boldsymbol{x}_n^a = \boldsymbol{x}_n^f + \boldsymbol{W}(\boldsymbol{y}_n - \boldsymbol{H}\boldsymbol{x}_n^f)$$

$\boldsymbol{W}$: Weighting Matrix

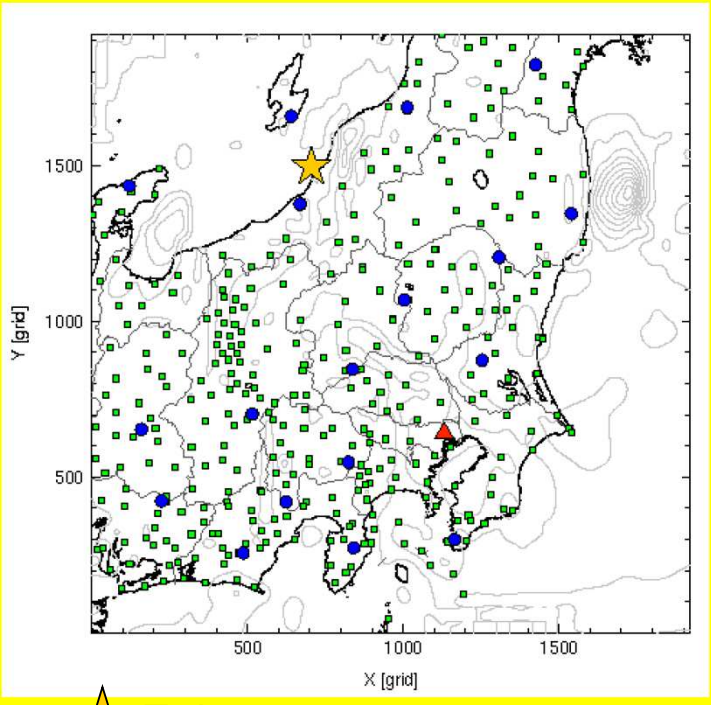
Comp. Assim.

$$\boldsymbol{x}_{n+1}^f = \boldsymbol{F}\boldsymbol{x}_n^a$$

$\boldsymbol{F}$: Wave Propagation simulation

Off Niigata 2007 Mw6.6 Earthquake

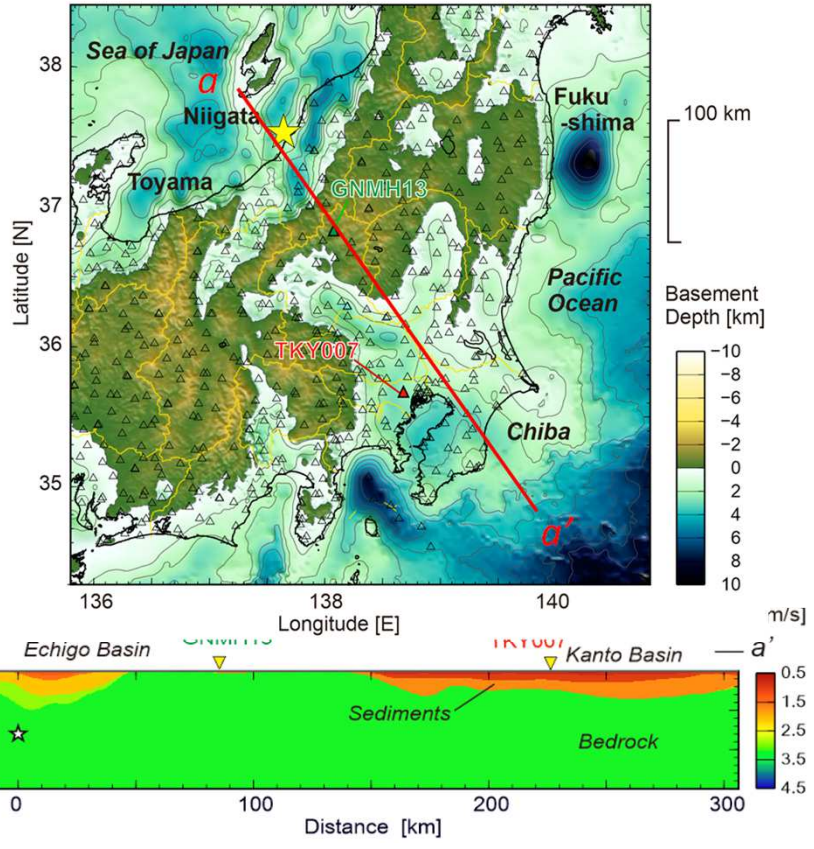
[c/o Prof. T. Furumura, ERI/U.Tokyo]



☆ Epicenter

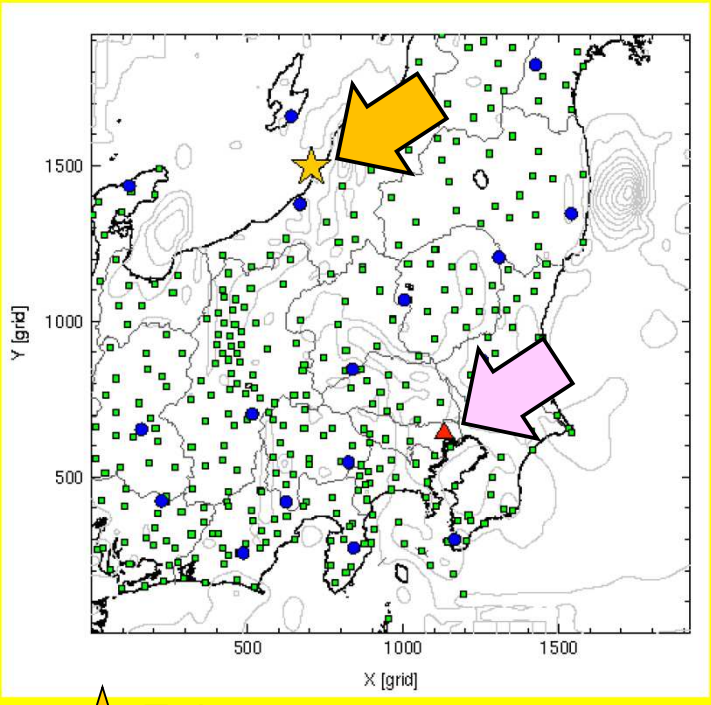
■ Hi-net (Short Period) 349 pts

● F-net (Broadband) 18 pts



Off Niigata 2007 Mw6.6 Earthquake

[c/o Prof. T. Furumura, ERI/U.Tokyo]



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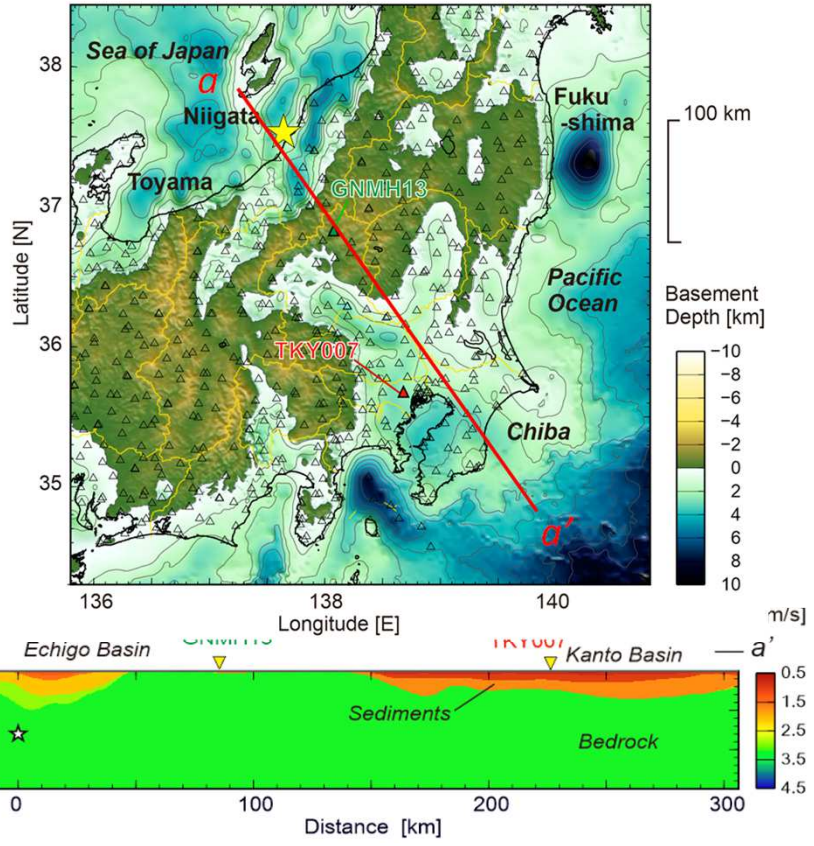
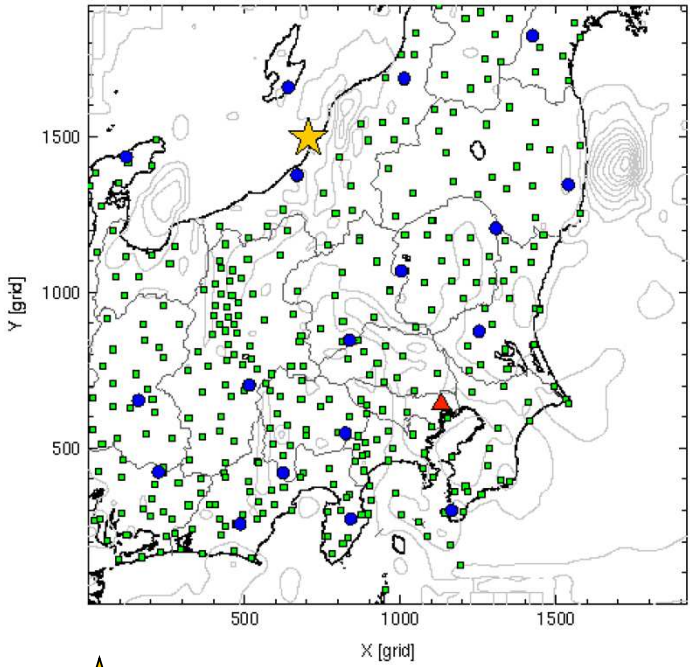


Off Niigata 2007 Mw6.6 Earthquake

[c/o Prof. T. Furumura, ERI/U.Tokyo]



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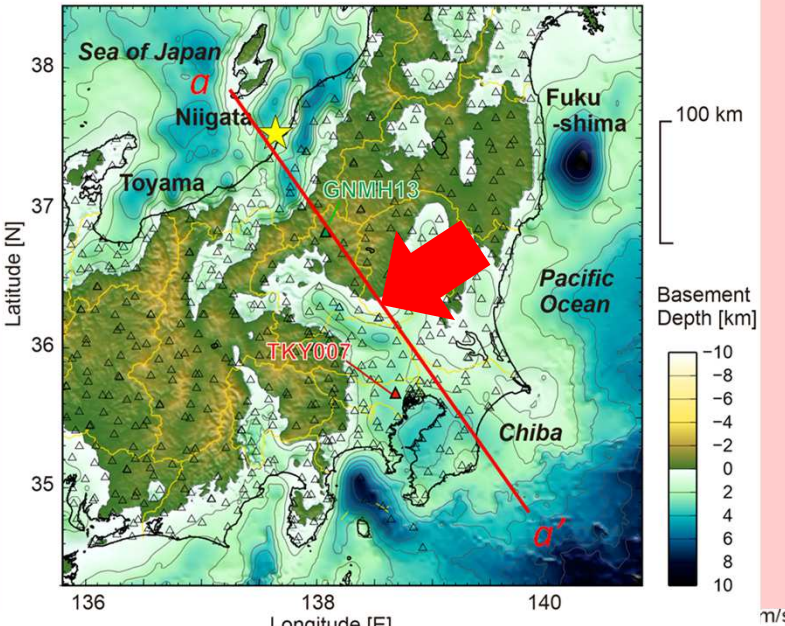
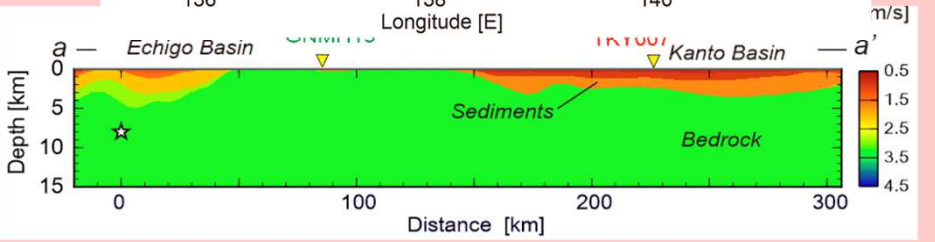
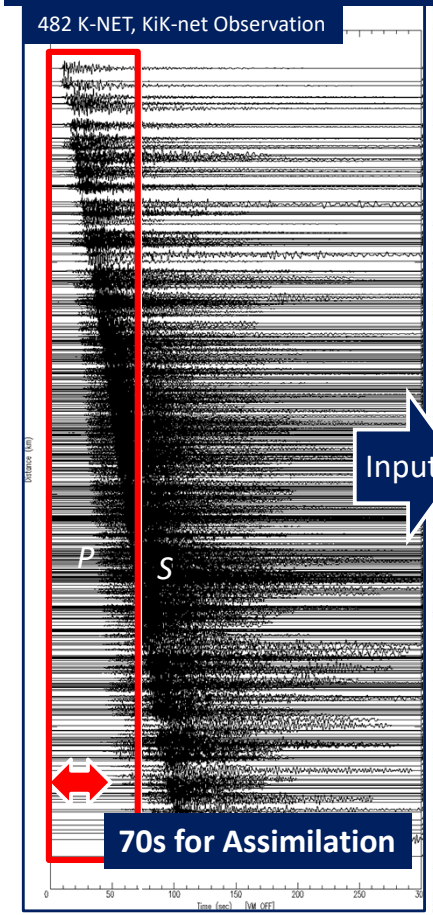
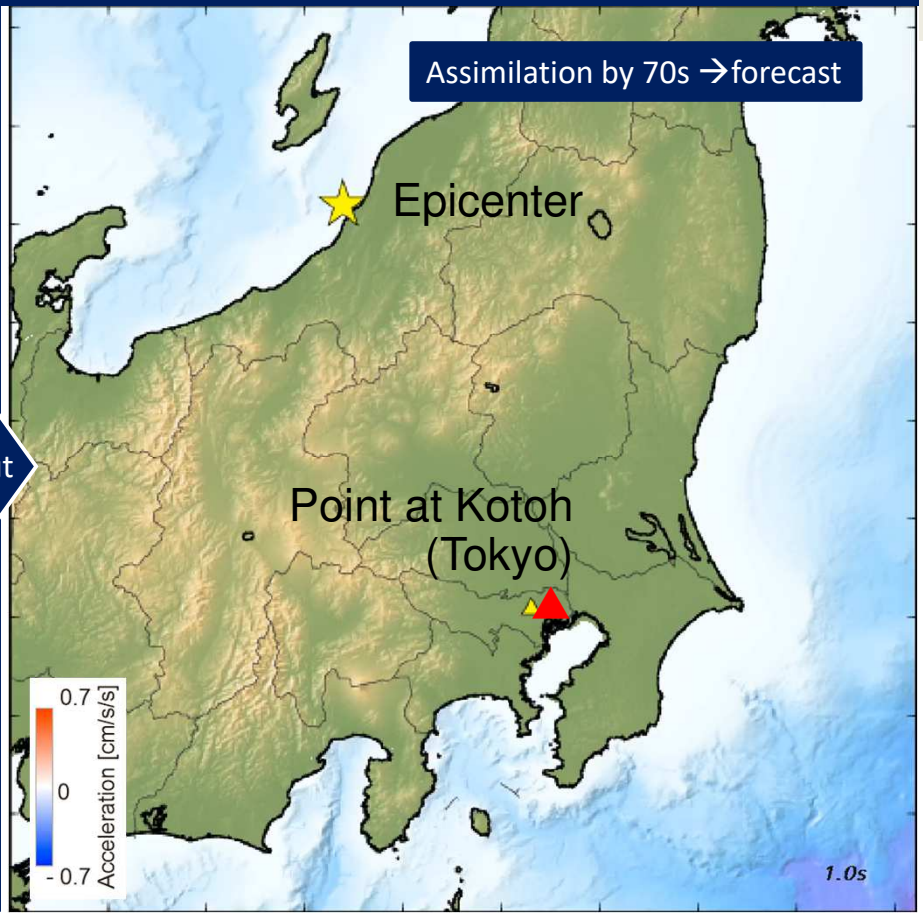


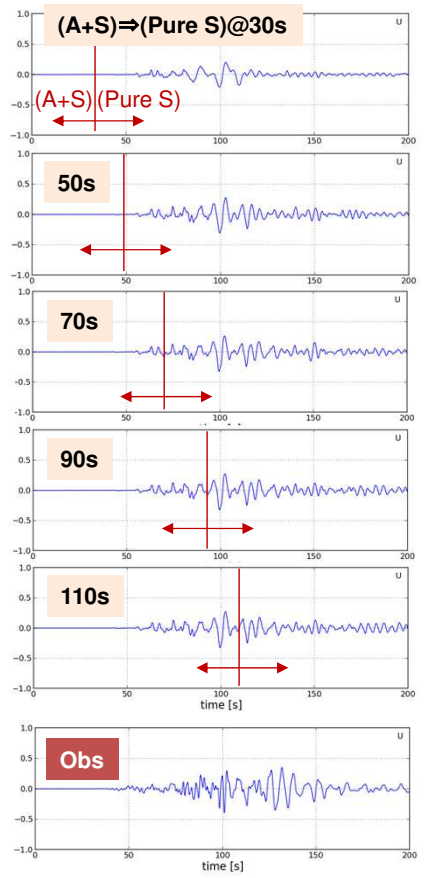


Data Assimilation + Pure Simulation/Forecast





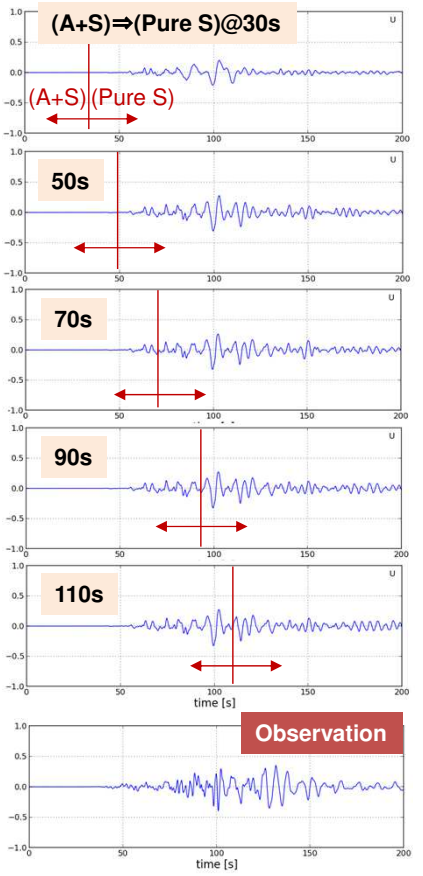
Results at Kotoh ▲ (N.KOTH)
N 35° 37.0'
E 139° 46.9'



Results: Off Niigata 2007 Mw6.6 Earthquake）

- (A+S)
  - Data assimilation is done using real-time observations, therefore this procedure cannot go ahead of real-time
  - Considering the overhead by preprocessing such as filtering, it is good to be able to calculate in about half the time of the actual phenomenon
- (Pure S)
  - 1/10 time of the actual phenomenon is required
  - Switching at 50 sec. from (A+s) to (Pure S)
  - If the subsequent 50 sec. can be computed in 5 sec., it is possible to predict the time when the peak wave will arrive in Tokyo, which is about 250km away from the epicenter (approx. 100 sec. after the occurrence of the earthquake)

Koto, Tokyo ▲ (N.KOTH)
N 35° 37.0'
E 139° 46.9'



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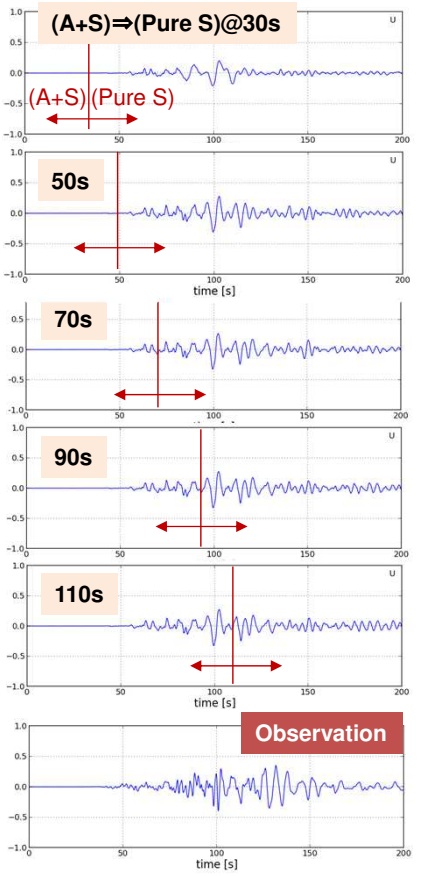

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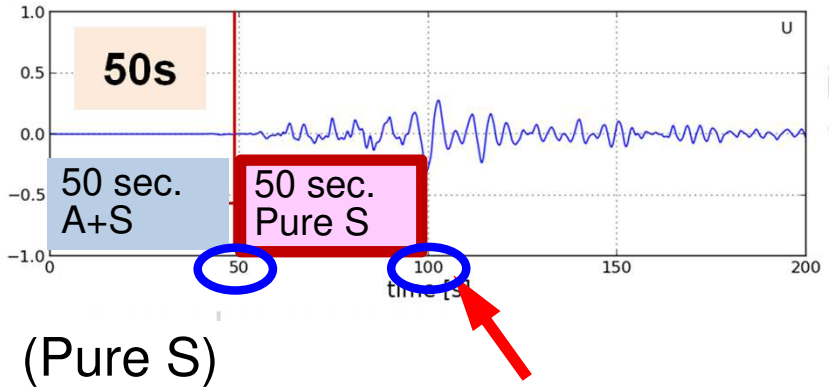

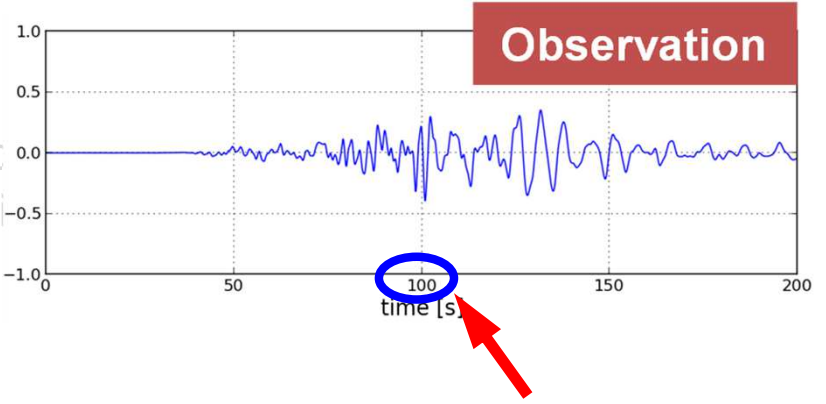

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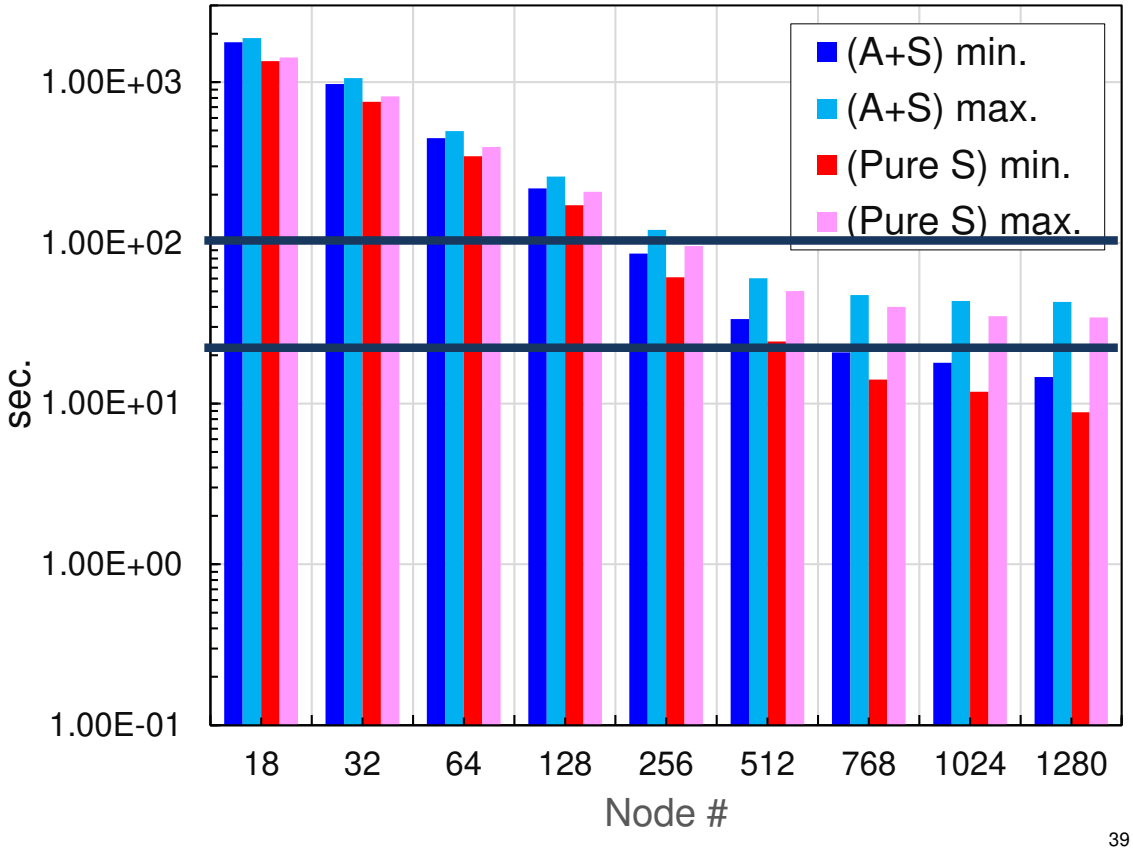
Computation Time for 200 sec. Phenomenon

- **Communications for I/O are included**
  - **min.: Comm. excluded**
  - **max.: Comm. Included**
- (A+S)
  - Computation in 100 sec. (Half of 200 sec.)
  - 300-400 nodes
- (Pure S)
  - Computation in 20 sec. (1/10 of 200 sec.)
  - 1,000+ nodes



Computation Time for 200 sec. Phenomenon

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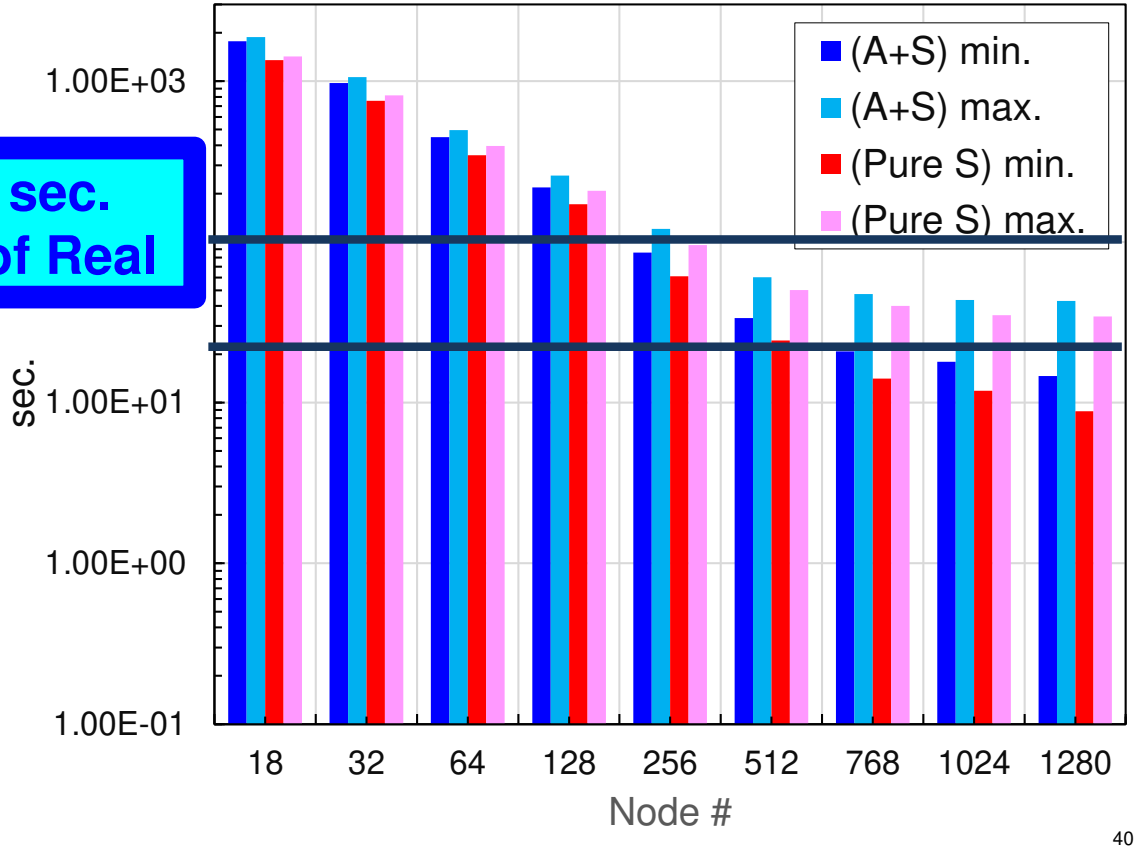
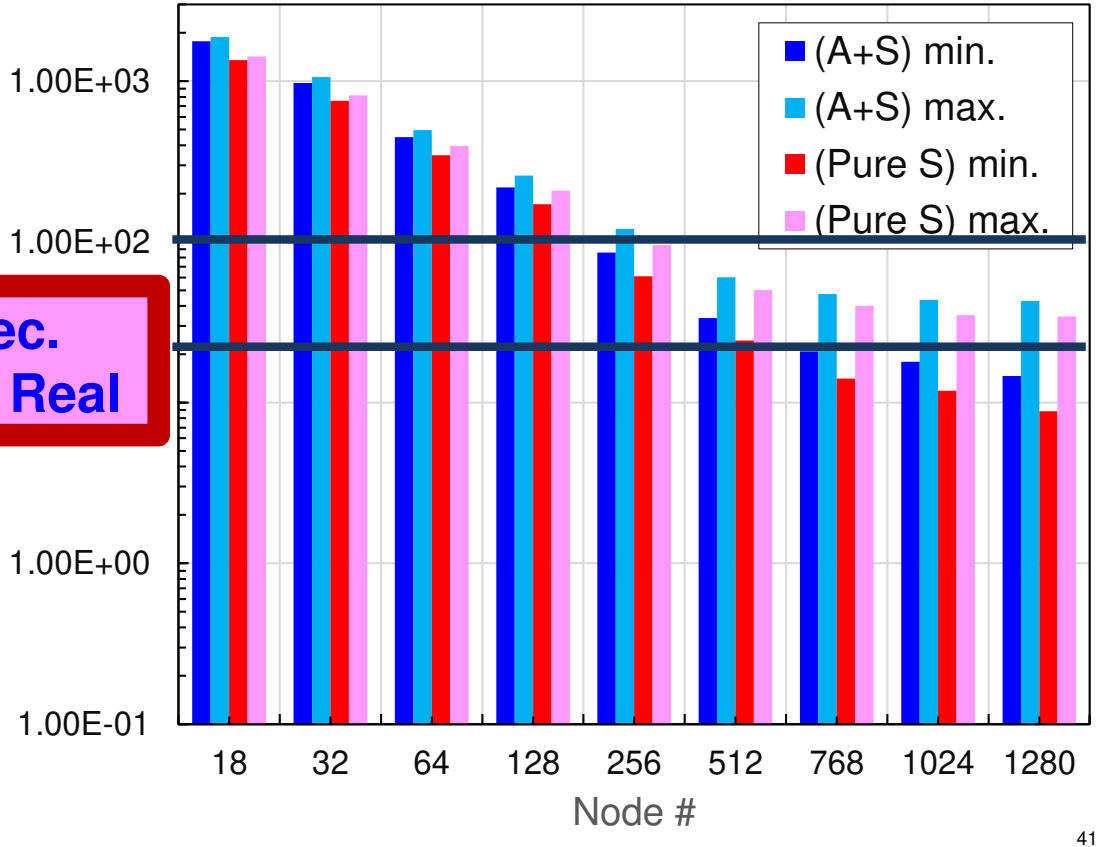
100 sec.
50% of Real



Computation Time for 200 sec. Phenomenon

- Communications for I/O are included
  - min.: Comm. excluded
  - max.: Comm. Included
- (A+S)
  - Computation in 1
    (Half of 200 sec.)
  - 300-400 nodes
- (Pure S)
  - Computation in 20 sec.
    (1/10 of 200 sec.)
  - 1,000+ nodes

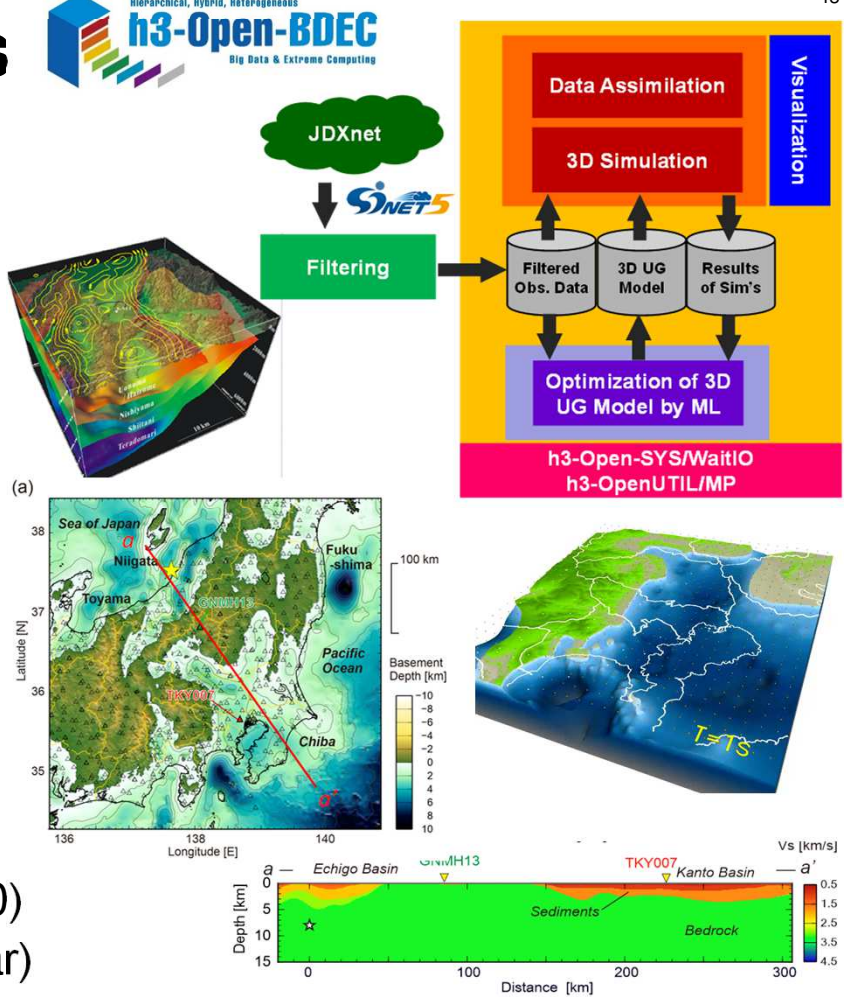
20 sec.
10% of Real



- Earthquake Simulation/Real-Time Data Assimilation
  - Seism3D/OpenSWPC-DAF by Prof. Furumura (ERI/U.Tokyo)
  - Preliminary Works on OBCX
- **The 3rd Pillar of h3-Open-BDEC**
  - **h3-Open-UTIL/MP**
  - **h3-Open-SYS/WaitIO**
- **Summary**

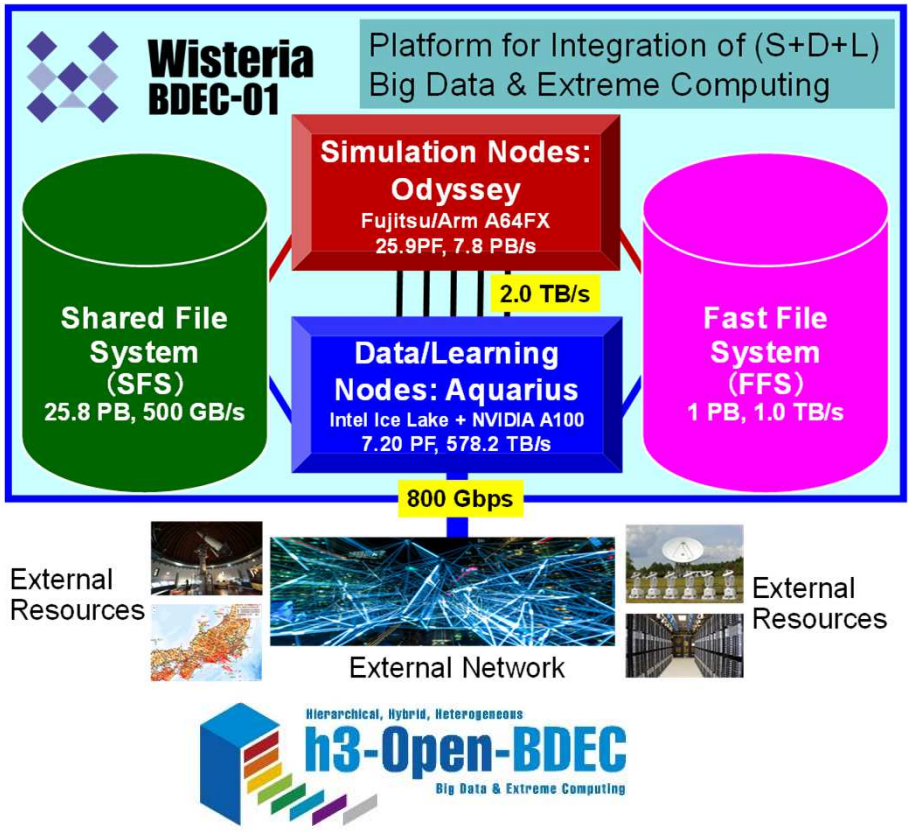
Future Directions towards Integration of (S+D+L)

- Accurate Prediction of Seismic Wave Propagation with Real-Time Data Observation/Assimilation
  - Emergency Info. for Safer Evacuation
- 3D Underground Model
  - Heterogeneous, Observation is difficult
  - Inversion analyses of seismic waves are important for prediction of structure of underground model
  - ML may be utilized for acceleration of this prediction based on analyses of small earthquakes in normal time (e.g. Mw < 3.0)
  - More sophisticated DA method (e.g. 4DVar)



Computing on Wisteria/BDEC-01

- **Wisteria/BDEC-01**
  - **Aquarius (GPU: NVIDIA A100)**
    - **Filtering, ML, Visualization**
  - **Odyssey (CPU: A64FX)**
    - **Data Assimilation, Simulation**
- Combining Odyssey-Aquarius
  - Single MPI Job over O-A is impossible



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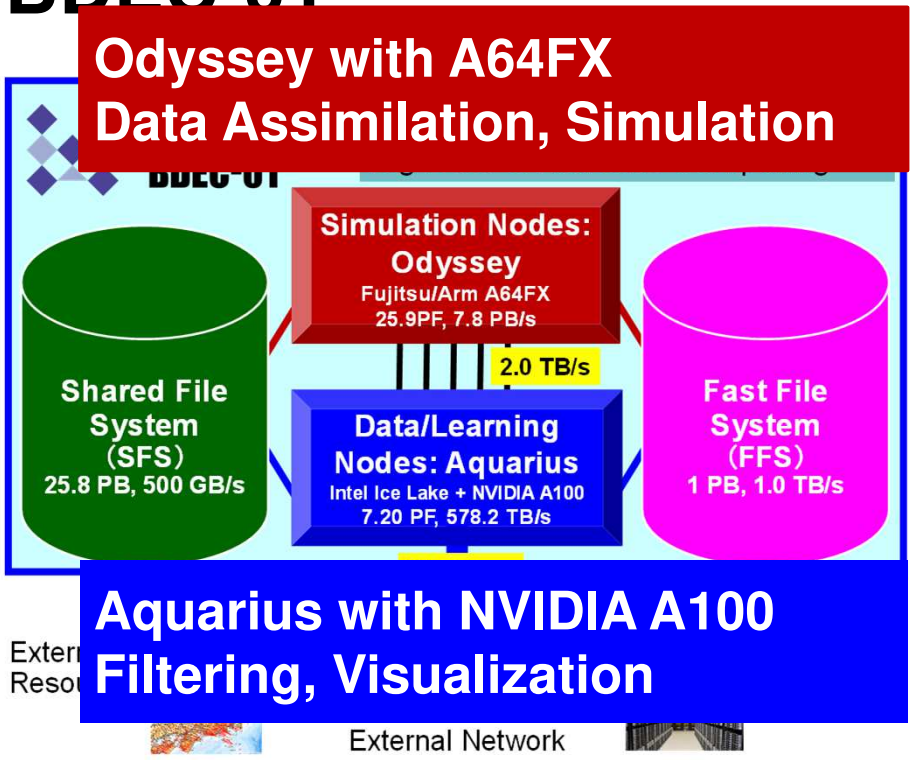
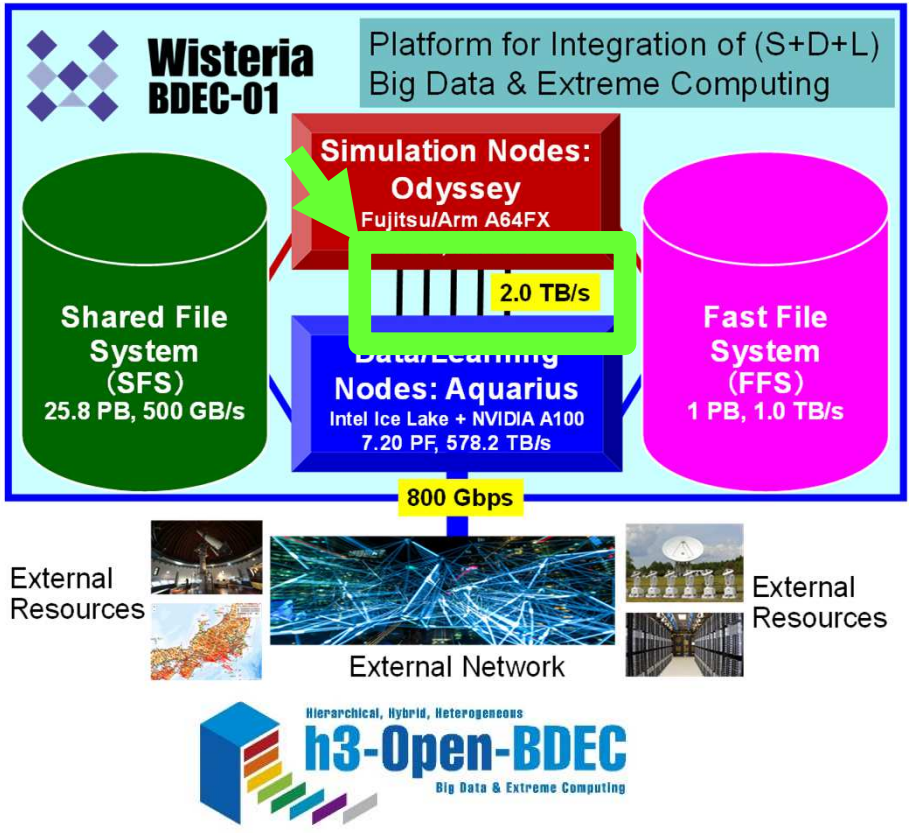


Hierarchical, Hybrid, Heterogeneous
h3-Open-BDEC
Big Data & Extreme Computing

Computing on Wisteria/BDEC-01

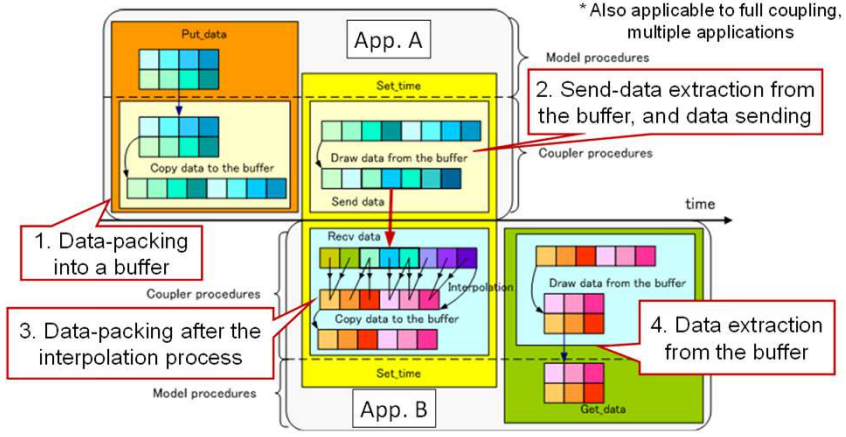
- Wisteria/BDEC-01
  - Aquarius (GPU: NVIDIA A100)
    - Filtering, ML, Visualization
  - Odyssey (CPU: A64FX)
    - Data Assimilation, Simulation
- Combining Odyssey-Aquarius
  - Single MPI Job over O-A is impossible
  - Actually, O-A are connected through IB-EDR with 2TB/sec.
  - h3-Open-SYS/WaitIO-Socket
    - Library for Inter-Process Communication through IB-EDR with MPI-like interface
  - h3-Open-UTIL/MP
    - Multiphysics Coupler



h3-Open-UTIL/MP

Multilevel Coupler/Data Assimilation

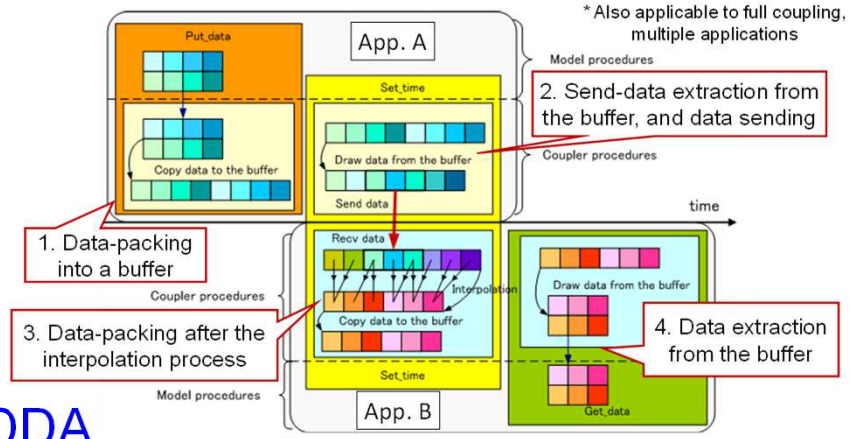
- Current Coupler: ppOpen-MATH/MP
  - Weak-Coupling of Multiple (usually two) Applications
    - Each application does a single computation



h3-Open-UTIL/MP

Multilevel Coupler/Data Assimilation

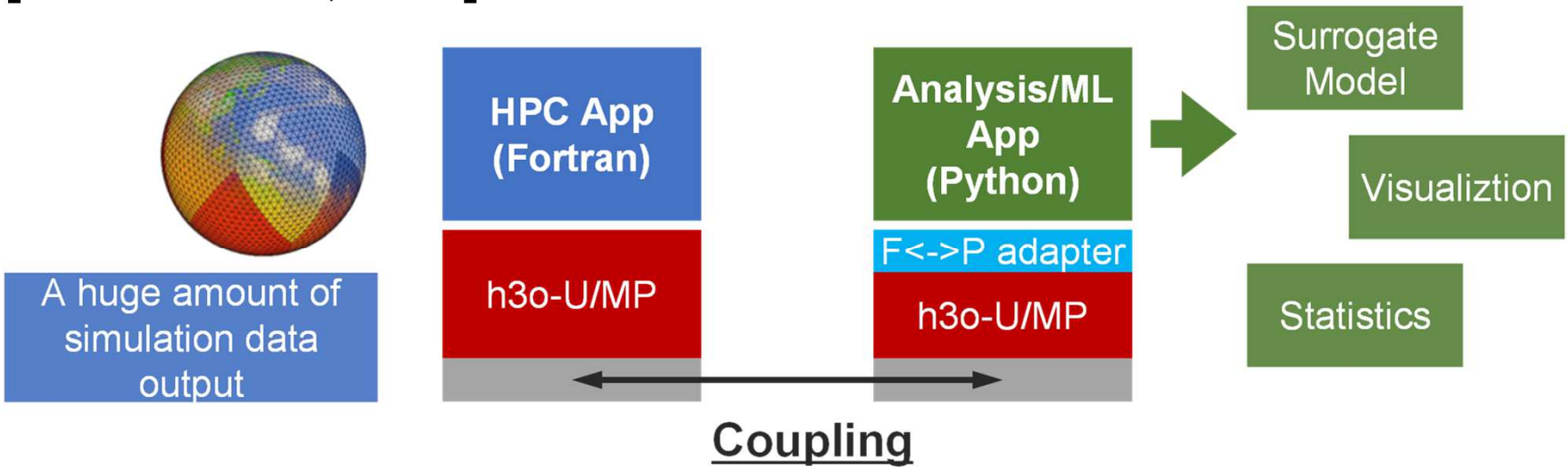
- Current Coupler: ppOpen-MATH/MP
  - Weak-Coupling of Multiple (usually two) Applications
    - Each application does a single computation
- h3-Open-UTIL/MP
  - Data Assimilation (Multiple Computations: Ensemble)
  - Assimilation of Computations with Different Resolutions
    - h3-Open-DATA, h3-Open-APP
  - Data Assimilation by Coupled Codes
    - e.g. Atmosphere-Ocean
- Data Assimilation: h3-Open-DATA
  - Karman Filter, Particle Karman Filter
  - LETKF
  - Adjoint Method
- Generation of Simplified Models in hDDA



h3-Open-UTIL/MP (h3o-U/MP)

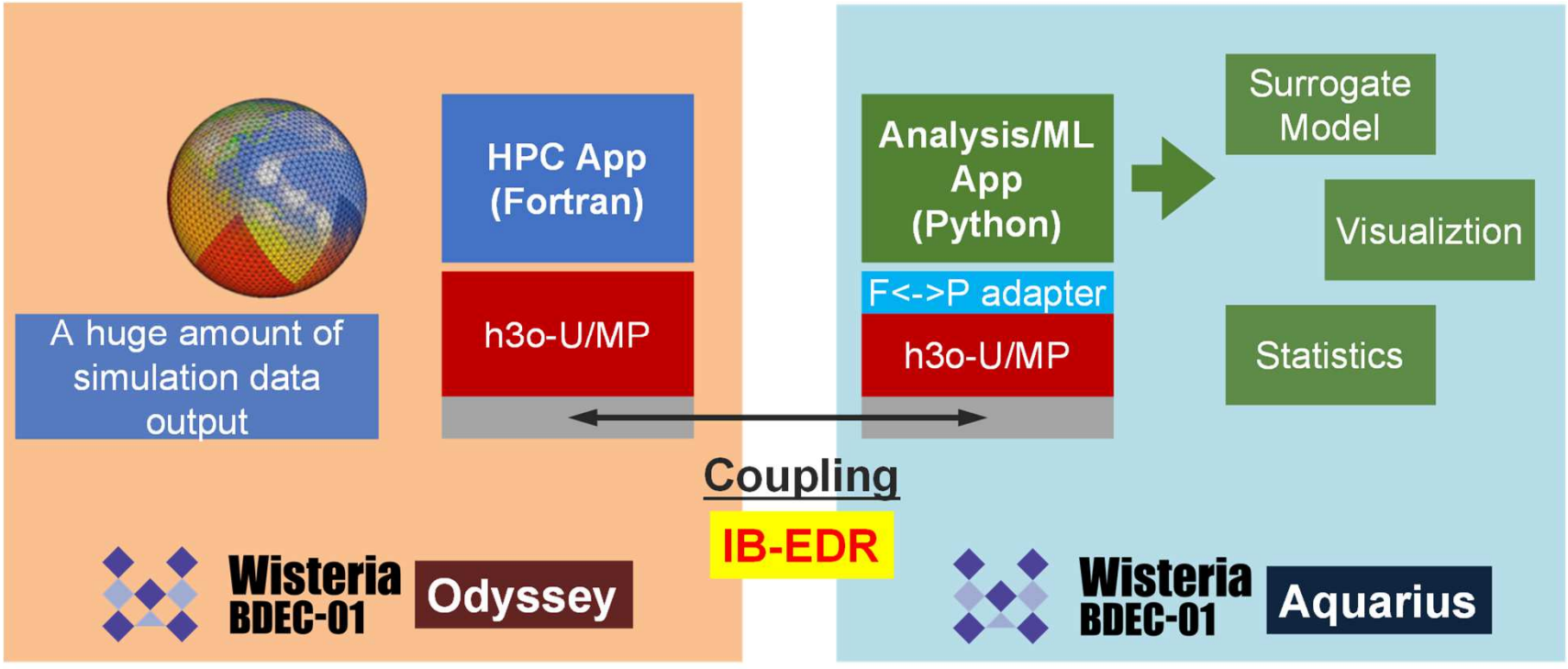
(HPC+AI) Coupling

[Dr. H. Yashiro, NIES]

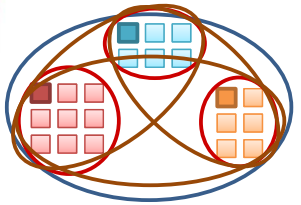


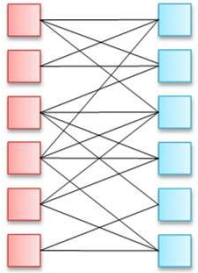
- Providing on-the-fly input/output/training data to the Analysis/ML tools
  - Easy to apply to existing HPC applications
  - Easy access to existing Python-based tools for AI/ML

h3-Open-UTIL/MP (h3o-U/MP) + h3-Open-SYS/WaitIO-Socket



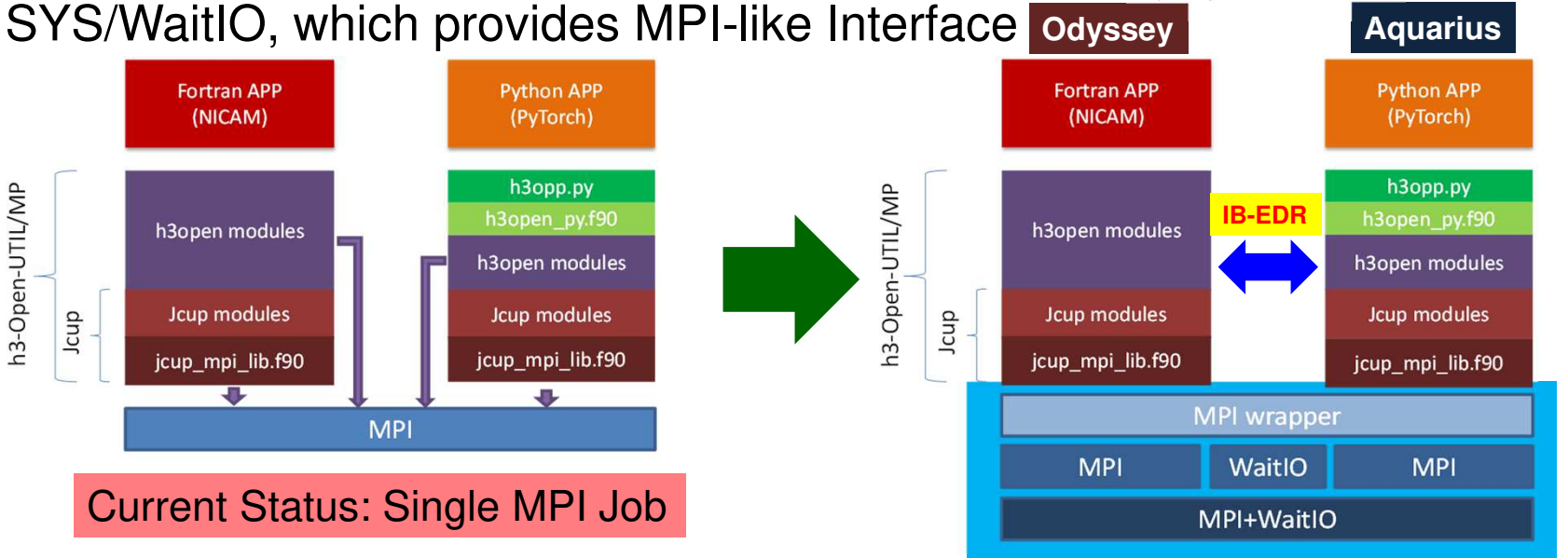
h3-Open-UTIL/MP + h3-Open-SYS/WaitIO-Socket





- Current Statue: Single MPI Job
- Direct Communication between Odyssey-Aquarius through IB-EDR by h3-Open-SYS/WaitIO, which provides MPI-like Interface

Wisteria BDEC-01

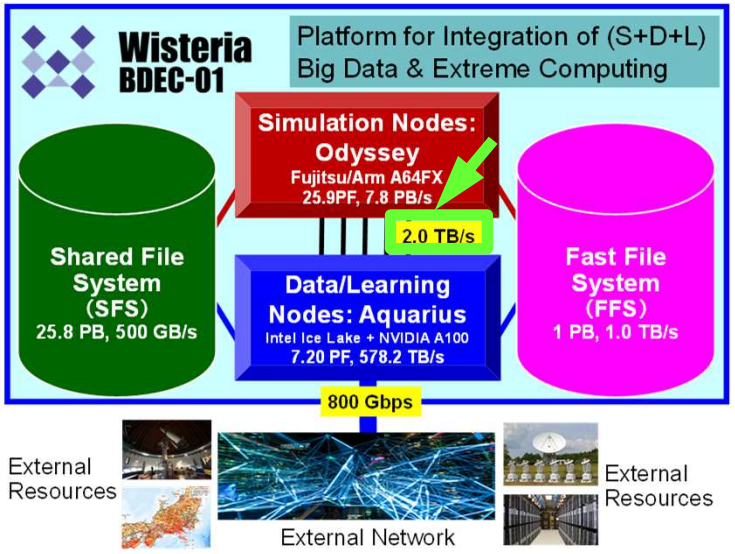


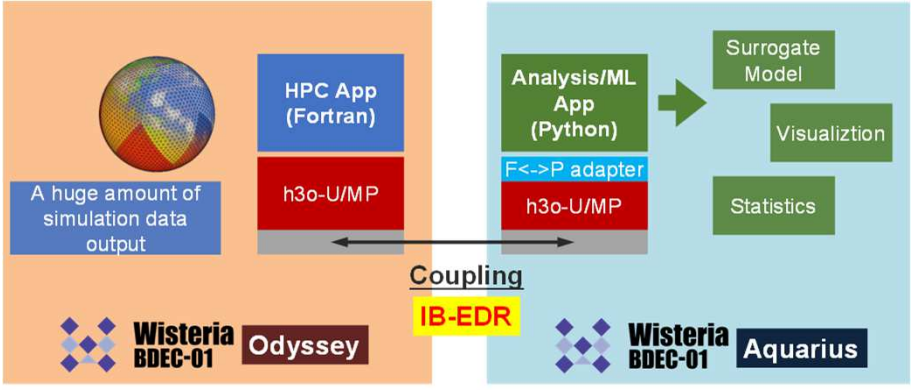
Current Status: Single MPI Job

Schedule for Public Use

Collaborations are Welcome !!

- h3-Open-SYS/WaitIO-Socket
  - Fall-Winter 2021, O-A Direct Communication by MPI-like Interface
- h3-Open-SYS/WaitIO-File
  - Via File System, FY.2022
- h3-Open-UTIL/MP（HPC+Python）
  - Fall-Winter 2021 on Odyssey only (Single MPI)
- h3-Open-UTIL/MP+h3-Open-SYS/WaitIO-Socket via IB-EDR
  - January-April 2022



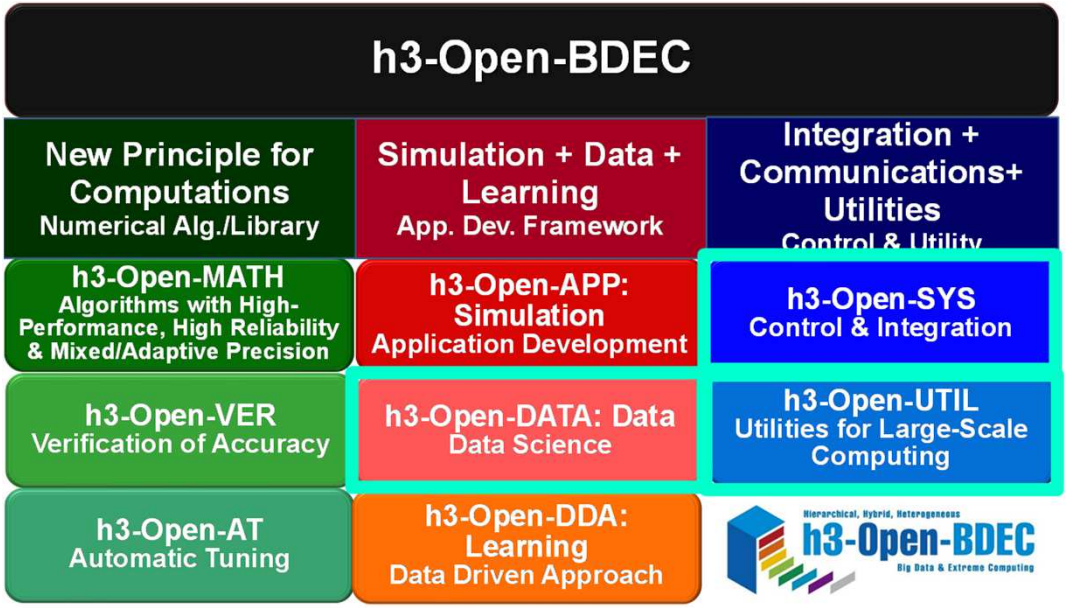


Wisteria BDEC-01

Hierarchical, Hybrid, Heterogeneous h3-Open-BDEC Big Data & Extreme Computing

Summary

- Earthquake Simulation/Real-Time Data Assimilation
  - On-Going Works for Real-Time Forecast/Assimilation
  - Preliminary Works on OBCX
- Future Works
  - Improvement of the Simulation Method
  - Improvement of Underground/Subsurface Model by ML (Machine Learning)
  - Extension to Wisteria/BDEC-01
  - More sophisticated algorithms for data assimilation (e.g. 4DVar, Ensemble 4DVar, 4DEnVar etc.)
  - Implementation/Optimization towards Real-Time System



1700-1720	Hiromichi Nagao (U.Tokyo)	Data Assimilation, Earthquake Simulation
1720-1740	Hisashi Yashiro (NIES, Japan)	h3-Open-UTIL/MP
1740-1800	Hiroya Matsuba (U.Tokyo)	h3-Open-SYS/WaitIO-Socket