

The contours of a trillion-pixel Digital Twin Earth

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Sveinung Loekken, Bertrand Le Saux, Sara Aparicio Φ-Lab, Future Systems Department Directorate of Earth Observation Programmes

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Digital twins



"A Digital Twin is a set of virtual information constructs that fully describes a potential or actual physical [system] from the micro atomic level to the macro geometrical level^{"1}

Applied to the planet

Not a new idea² ...



"...an interactive digital replica of the entire planet that can facilitate a shared understanding of the multiple **relationships between the physical and natural environments** and society."

Examples OneGeology4.0



Digital Twins for the next generation of geoscience prediction and understanding

NASA



NASA's Digital Earth Visualization studio, addressing some of the elements of a Digital Twin Earth



ISDE

International Society for Digital Earth (<u>http://www.di</u> <u>gitalearth-</u> isde.org/)

1. M. Grieves and J. Vickers (2016). Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems 2. Manual of Digital Earth, Huadong Guo, Michael F. Goodchild, Alessandro Annoni, Springer Nature 3. www.onegeology.org

Why a Digital Twin of the Earth in Europe now?





The short answer

Take a giant step towards a prognostic decision support capability in the context of policies for sustainable development



Respond to and support European policy

The **European Green Deal**², aimed at achieving a carbon-neutral society by 2050, calls for the "EU's ability to predict and manage environmental disasters". The new **EU Data Strategy**³ proposes to Launch the "Destination Earth" initiative, to "…*bring together European scientific and industrial excellence to* **develop a very high precision digital model of the Earth**. This will offer a digital modelling platform **to visualize, monitor and forecast natural and human activity on the planet in support of sustainable development**...".



Provide a big push for advances in EO-related technology and science

Progress is required to implement the DTE The DTE provides the objectives, resources and challenges/objectives for scientists and technologists to progress



Because now we can: preconditions are finally (mostly) in place

Push from policy, Observing system (Copernicus, Met missions, National missions, New space, IoT ...); ICT, infrastructure investments; big data methodology and AI

2 European Commission COM(2019) 640 final, 11 December 2019 3 European Commission COM(2020) 66 final, 19 February 2020

Contours: what could a trillion pixel DTE look like?

DTE Definition: a **dynamic interactive replica** of the **past, present and future** of our planet in the digital domain, based on an effective integration of **observations** (satellite, in-situ, <u>IoT</u> and socioeconomic data), **Earth-system science and simulations**, the bridge to **impact sectors science and simulations** and **artificial intelligence methodologies**



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European Space Agency

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Contours: what could a trillion pixel DTE look like?





Science/physics-based

Will arise from the integration and enhancement of existing building blocks that accurately reflect diverse physical aspects of our planet, such as satellite observations, data assimilation frameworks and Earth-system models

Applied and end-to-end

Requires the full convergence of Earth-system simulation and socioeconomic impact science, Earth observation and the breadth of future digital technologies

Can address many societal challenges

Initially key axis targeted by the European Green Deal



Emergency and risk management











Renewable energy

*

Challenges (I), targets



To deliver according to purpose, the DTE must¹:



Seamless link

Guarantee

Ouality

Deliver a break-through in accuracy and realism: more reliable and detailed information about past, present and future changes in the Earth system, overcome key sources of model errors and key gaps in observational capabilities



Integrate ES componemnts of impact sectors at the source of data production: to impact sectors Earth-system components of impact sectors need to be fully integrated (e.g. hydrological processes for water, vegetation-soil processes for food, wind-waves-solar processes for energy, dispersion-air quality for health, etc.)



Optimally fuse observations and models: there are substantial measurement gaps (horizontal coverage, both vertical and horizontal resolution, missing Earth-system observables such as wind, deep ocean currents) that can only be filled by models



Provide rigorous handling of guality and confidence information: given the uncertainty in observations and models



Develop and use the full capabilities of the new digital continuum, Given the growth scales needed to generate and manage a realistic and reliable Digital Twin of aspects of the Earth system the extreme-scale capabilities of the entire digital continuum are needed

1. White Paper - Digital Twin Earth, DRAFT v 5 June 2020, (Internal ESA/ECMWF), P. Bauer and M. Rast

Challenges (II), AI/ML related



1000	Sheer volume	Earth is the biggest system that humans have tried to replicate (is it ?), data skyrocketed. Machine learning to speed up compute and simulations ML and ESM challenge: Integrate ML and physics-based models ¹
Ţ.	Methodological Chasm	Physics- (and biology and chemistry) based earth sciences vs. correlation/statistics based ML. ML challenge: How to have physical-ruled ML? Explainable AI, causality. ESM challenge: How to trust AI models?
	Data heterogeneity	ML will be key in handling variety of data types, data sources and sensors. ML challenge: How to perform data fusion and assimilation of such different data? ESM challenge: How to separate what is dependent from what is unrelated?
└ <u>₩</u> └ <u>₩</u> ĸŋ) -	Heterogeneity _H of scale	Models and observations at various resolutions; sparse/ graph vs. dense data. AI as a way to perform data assimilation and information propagation. ML and ESM challenge: How to mix scales?
in the second se	Temporality & data gaps	DTE to analyze phenomena over time, time series means causality ² , influences of factors ML challenge: causality instead of correlation ESM challenge: how to encode models in ML-based simulations?
-	Supervision	Mostly continuous regression tasks, without direct supervision ML challenge: unsupervised and semi-supervised learning ESM challenge: derive potential supervision from physical rules, (self-supervision)
1 M. Reichstein et al (2019), Deep learning and process understanding for data-driven Earth system science, Nature VOL 566 2 J. Runge et al (2019),Inferring causation from time series in Earth system sciences, Nature communications, https://doi.org/10.1038/s41467-019-10105-3		

Challenges (III), AI/ML related



Phenomenon
discoveryHow can DTE help us to discover relations and triggers in the flow of events?
ML challenge: Real, big scale statistic (measures, layers, noise and correlations, can lead to
generative modeling)
ESM challenge: Accept to deconstruct models (accepting data mining correlation and suggestion
from statistical correlation)and let emerge new ones. relaxation of assumptions from the ESM side.ForecastingHow to predict the evolution of Earth, and Earth variables (temperature, weather, sea, vegetation)?
ML challenge multi-temporal, high dimensional (X*4D) modelling.
ESM challenge: : simulation at a new scale, with long term forecasting.Link to impactDTE to address the themes of the Green Deal, how to integrate Earth science data and models with
socioeconomic data and models?

ML challenge: modelling of exchanges, moves through graphical modelling, graph neural networks. **ESM challenge:** incorporate new fields from impact sectors, Earth observation at high resolution, urban EO...

Updating

sectors

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Continous evolution and improvement, how to change and improve the DTE and its models over time? ML challenge: reinforcement learning, continuous learning

Challenges (IV), others





DTE requires state of the art ICT (as well as future advances), how to eliminate inefficiencies in use of modern HW infrastructure, benefit from e.g. cloud + HPC, move to new paradigms of computing.



How to design user interfaces and interaction models for Big Data¹ (and the DTE)? User interaction models and processes fit for multiple purposes and user categories – from explorative mixed reality through platform interfaces to command line. Need HCI.

1. Chunpir, Hashim & Williams, Dean & Ludwig, Thomas. (2017). User Experience (UX) of a Big Data Infrastructure. 467-474. 10.1007/978-3-319-58524-6_37.

Pitfalls: a few surprisingly hard non-technical issues





`DTE as a label': the risk of relabeling of existing and planned activities, need a central, clear and unifying objective



Intelligent reuse and fit-for-purpose: public money means economic and political necessity to reuse existing capabilities and benefit from previous investments, but must develop where needed and ensure that components are fit for purpose

Federation vs. excessive fragmentation: specific requirements in the thematic domain, but not lose sight of the whole – DT <Ocean + Atmosphere + lithosphere + ... > versus Digital Twin **Earth**. Risk to lose the synergy and holistic vision of the overall earth system, which we are addressing



Communities' vs silos – it has proven surprisingly hard to attract e.g. the AI community to earth observation data; same for science to industry.



Finally, the DTE will not exist in a moral vacuum, to undertake an endeavor of this magnitude we must address issues of societal impact of the DTE itself - ethics, privacy and security ...

DTE as a game changer for EO



Mission oriented R&I¹, relevance and impact: anchored in policy, grand challenges of humanity

Increased uptake of EO, also in new application domains: new disciplines exposed to EO data and information products, also outside traditional domains. Out of the physical/biological/chemical universe and into socioeconomic impact sectors

Forces the engagement of multi- and inter-disciplinary communities: the remote sensing, earth sciences, the AI crowd, social scientists from impact sectors, computer scientists, HCI people and data scientists are all needed

Balances capabilities on ground with capabilities in space: amazing observing system, **but data is a LIABILITY** until we extract relevant information from it, to date much less investment on the exploitation of data. Staying abreast of the observing system.

Evolution of the EO 'User segment' and related use scenarios: from FTP through platforms to DTE. The dominating exploitation scenario is still 'download and process at home'. This is a Neolithic scenario.

Removes long-standing obstacles to full-on EO data exploitation: Will have to address a number of shortcomings that have hampered the uptake and impact of EO data, e.g. training data, analysis ready data, the systemic and SW developments that allow for a better use of hw infrastructures, required advances in AI to take off on EO

1. M. Mazzucato, (2018), Mission-Oriented Research & Innovation in the European Union _ A problem-solving approach to fuel innovation-led growth,

Happening at ESA

ESA and ECMWF refining the DTE concept

• DTE white paper^{1,} a proposition for a baseline, non-normative, conceptual common understanding

Participation in a working group set up by the EC

• DG-CNCT, ECMF, ESA, certainly others ...

ESA DTE pre-cursors

- Thematic precursor: prototyping 4 'instances' of DTE, from 4 of the Green Deal thematic domains
- AI4DTE study: addressing the integration and use of AI/ML in the DTE, resulting research
- DTE simulation on local scale: dynamic DTE
- DTE topic in Phi-lab visiting professors scheme

The EU developing the Green Deal call

• e.g. 'A transparent & accessible ocean: Towards a Digital Twin of the Ocean'2





1 "White Paper - Digital Twin Earth", DRAFT v 5 June 2020, (Internal) P. Bauer and M. Rast 2 https://ec.europa.eu/info/research-and-innovation/strategy/european-green-deal/call/strengthening-knowledge_en



Summa Summarum

The DTE is a **moon-shot** that can **stimulate advances** in EO, science & technology, reinforce relevance by building the bridge to impactful socioeconomic sectors associated with the **grand challenges of humanity**

It can be a **giant step towards a prognostic decision support capability** for sustainable development policy, representing the most **momentous use-case for EO**

It poses a number of **Inspiring technical challenges** (and some less inspiring Pitfalls),

... the DTE is also an intellectually stimulating concept: "Time-To-Matrix" (TTE) and the really big objectives

DTE is a moonshot

"Optimistic, aspirational and courageous we must be" - Yoda



Thanks





[Sveinung.Loekken,Bertrand.Le.Saux,Sara.Aparicio]@esa.int

