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Editorial

Next-Generation Digital Earth*

A position paper from the Vespucci Initiative for the Advancement of Geographic Information Science

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Abstract

This position paper is the outcome of a joint reflection by a group of international geographic and environmental scientists from government, industry, and academia brought together by the Vespucci Initiative for the Advancement of Geographic Information Science, and the Joint Research Centre of the European Commission. It argues that the vision of Digital Earth put forward by Vice-President Al Gore 10 years ago needs to be re-evaluated in the light of the many developments in the fields of information technology, data infrastructures, and earth observation that have taken place since. It focuses the vision on the next-generation Digital Earth and identifies priority research areas to support this vision. The paper is offered as input for discussion among different stakeholder communities with the aim to shape research and policy over the next 5-10 years.

Keywords: Digital Earth, spatial data infrastructures, Earth Observation, GEOSS, geobrowsers, voluntary geographic information.

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1. Introduction

Ten years ago, U.S. Vice-President Al Gore articulated a vision of “Digital Earth” as a multi-resolution, three-dimensional representation of the planet that would make it possible to find, visualize, and make sense of vast amounts of geo-referenced information on the physical and social environment. Such a system would allow users to navigate through space and time, access to historical data as well as future predictions based for example on environmental models, and support access and use by scientists, policy-makers, and children alike (Gore 1998).

At the time, this vision of Digital Earth seemed almost impossible to achieve given the requirements it implied about access to computer processing cycles, broadband internet, interoperability of systems, and above all data organization, storage, and retrieval. As an example, with the technology then available, it was going to take more than 100 years to download the data needed to cover the Earth’s surface at 1 meter resolution, and more than a human lifetime to view it.

Ten years later, many of the elements of Digital Earth are not only available but also used daily by hundreds of millions of people worldwide thanks to innovative ways to organize and present the data and rapid technological advancements[1]. Geo-browsing (browsing digital geographic information over the web) has become a major industry[2] and introduced novel ways to explore data geographically, and visualize overlaid information provided by both the public and private sectors, as well as citizens who volunteer new data (Goodchild, 2007). Several major initiatives, discussed later in this paper, have also been launched at regional and global levels to increase our capacity to observe and understand our planet, its environment, and the impacts on and by society.

It is now time to ask: has the vision of Digital Earth been achieved? Has the Grand Challenge been met? This paper argues that it has not, because in parallel to increased availability and access to information, our collective awareness of the need to understand interdependencies of environmental and social phenomena on a global scale has also increased. Major natural disasters like the Indonesian Tsunami (2004), Hurricane Katrina (2005), and the Sichuan earthquake (2008) to name but few have contributed to this raised awareness, together with mounting evidence from the Intergovernmental Panel on Climate Change (www.ipcc.ch) of the profound changes occurring in our ecosystem, and

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[1] These advancements include graphics co-processors with as much as 512 MB dedicated memory (in 1998 64MB was predicted), clever server-side data caching, and multiresolution techniques allowing for storage and progressive visualization of multiple Levels of Detail (LOD).

[2] Although the market now seems quite large in terms of number of user, commercial geobrower makers admit that these services have yet to be “monetised” via advertising or subscription fees.

the cost of non-action, estimated at a minimum of 5% of global GDP year on year (Stern, 2006). Also technological expectations have risen over the past decade: ordinary web users now expect information, from anywhere and about anything, to be easily and quickly accessed, raising the bar for scientists and technologists to properly organize, represent, and then serve, such data.

The more we understand the complexity of interactions and inter-dependencies between environmental and social phenomena at different levels, local, regional, global, the more we need dynamic information systems to provide reliable, accurate, timely, and openly accessible information at the relevant geographic and temporal scales. The more geographic information we have, the more we see the need for sophisticated processing and analysis models that can turn information into insight and intelligent action. It is now necessary therefore to take stock of current developments and refocus the vision towards the next generation Digital Earth.

2. Key Developments since Digital Earth

It may be useful to group key developments of relevance to this paper into four related themes.

2.1: Organizing Geographic Information

This theme includes the many initiatives since the early 1990s aimed at increasing the availability and accessibility of geographic information through the development of spatial data infrastructures (SDIs). By the mid 1990s, Masser (1999) identified at least 11 SDIs at varying stages of development spanning large countries like the USA, Canada, and Australia, small ones like the Netherlands and Portugal, and developing nations like Malaysia, Indonesia, and Qatar. That first generation of SDIs was largely led by national mapping agencies and oriented towards the completion of national spatial databases addressing topography and other key layers of general use. The documentation of existing resources via metadata, and access mechanisms via catalogues and clearinghouses were other key features of these early developments.

Since then we have seen a rapid diffusion of SDIs world wide facilitated by the establishment in 1996 of the Global Spatial Data Infrastructures Association[3] that has helped the promotion of best practice and sharing of experiences, and capacity building in the Americas, Africa, Asia and the Pacific and Europe. In Europe a major recent development has been the adoption of a legal framework in 2007 to establish a distributed Infrastructure for Spatial Information in Europe

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[3] www.gsdi.org

(INSPIRE)[4] built on the SDIs of the 27 Member States of the European Union. At the international level, it is also worth noting that in 2006 the UN Geographic Information Working Group (UNIGWG)[5] developed the vision, strategy and the institutional governance framework for a United Nations SDI initiative. In its initial phase (2008-2010) the UNSDI initiative is project-based, defined around projects outputs that can involve non-UN partners but in the medium-term the UNIGWG membership recognizes that the UNSDI will require legislative legitimacy.

The nature of these more recent SDIs has also shifted with an increased number of stakeholder organizations engaged in the process. There is also a stronger emphasis on distributed data and processes, and the interoperability of services to discover, view, access, and integrate spatial information. The interoperability of systems through services has been the major focus of the Open Geospatial Consortium[6] established in 1994 as an international partnership between government agencies, industry, and academia. The OGC client-server interface specifications and the standards adopted by the International Standards Organization (ISO) have become the cornerstone of most SDIs in their current form. In spite of this greater emphasis on interoperability through services, the underlying basic approach to a SDI architecture has not evolved much during the last 10 years.

2.2: Geography as a way to organize information

This theme includes the development of geo-browsers (e.g. Google Earth, Microsoft Virtual Earth, NASA Worldwind, ESRI ArcGIS Explorer) which use the globe as mechanism to pan, zoom, and fly over the Earth's surface to areas of interest much as in the original vision of Digital Earth. Associated to these 3D representations of the Earth are also 2D applications (Google Maps, Microsoft Live Search Maps) that also allow users to add and share information via simple Application Programming Interfaces (APIs). Beyond visualization however, geobrowsers have become client applications for accessing a more complex infrastructure behind the scenes and for fulfilling a wider goal: organizing the world's information, in part spatially (Jones 2007).

Grossner et al. (2008) identify the "Digital Earth Initiative" (DEI) chaired by NASA as a key milestone in trying to put the Al Gore vision into practice. The initiative involved a number of US federal agencies and ran between 1998 and 2001 focusing on interoperability, infrastructure and organizational issues. A major step forward came from the commercial sector in 2001 with the launch of Keyhole's Earth Viewer that demonstrated the technical feasibility of providing a global view

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[4] www.ec-gis.org/inspire
[5] http://www.ungiwg.org/
[6] www.opengeospatial.org

of the world using imagery on desktop computers, further enhanced by the increased availability of powerful graphics cards in standard PCs. Google acquired Keyhole in 2004 and launched its Google Earth in 2005, the same year also making available its API for Google Maps thus making it possible for anybody to add information to the Google platform. The Keyhole Markup Language (KML) has also become a powerful way to document and index information with a geographic reference, and display it on maps or globe interfaces. The declared aim of Google is therefore not to organize geographic information (as in SDIs) but to use geography as a way to search and view information with a geographic footprint.

The success of Google Earth and Google Maps with hundreds of millions of users, spurred Microsoft to accelerate its own developments and release at the end of 2006 its alternative products, with a stronger emphasis on 3D visualizations, particularly in urban areas. In parallel ESRI released a viewer (ArcGIS Explorer) for its main GIS software platform also based on the globe metaphor.

It is not to be unexpected that users focus their attention on the geobrowser client, for after all it is this which must be installed on their desktop machine and allows them to interact with geographic information. However, a strong case can be made that the loosely connected information model, based on the standard web architecture which allows geodata to be both found and published and the servers that host data and process client requests are actually more important. We could refer to this as the GeoWeb infrastructure to provide contrast to the traditional SDI approach. The technical breakthroughs in horizontal (multiple machines) and vertical (multiple hardware/software tiers, together with data caching mechanisms have perhaps been the major contribution to the success of the technology platforms and the biggest revolution in information organization and access in many years.

Although these developments have been led by the private sector on a commercial basis, their widespread success has also led an increasing number of public-sector agencies to use these platforms to visualize their data. Examples in this respect are the Cadastre of Spain[7] and the European Environment Agency[8]. Also worth mentioning is the leadership taken by China in promoting a bi-annual International Symposium on Digital Earth starting in 1999. Since 2006 China acts as Secretariat to the International Society for Digital Earth[9] promoting

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[7] http://www.catastro.meh.es/servicios/wms/wms.htm#_Buscar_parcelas_en_Google_Earth

[8] http://www.eea.europa.eu/highlights/eea-and-microsoft-will-bring-environmental-information-to-your-fingertips

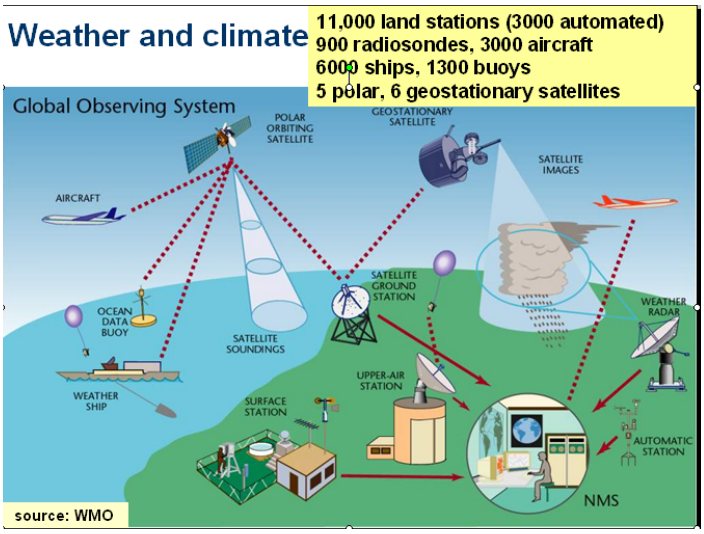
[9] http://www.digitalearth-isde.org/

international collaboration and scientific exchange to achieve the vision of Digital Earth.

2.3:Geosensing the World

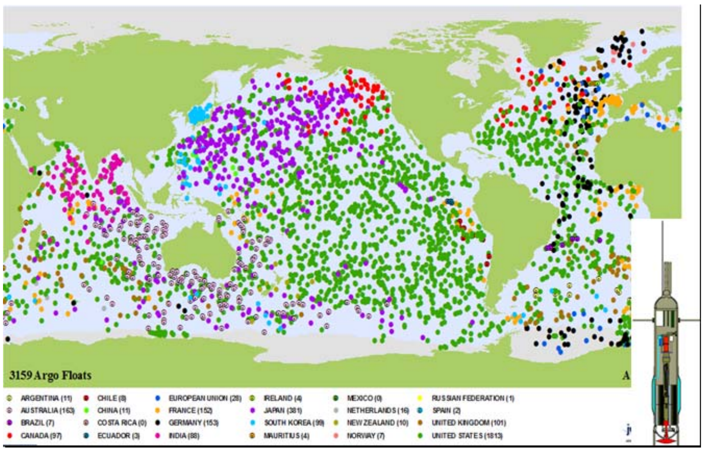
Geosensors can be defined as any device receiving and measuring environmental stimuli that can be geographically referenced. As such they include satellite-based sensors providing multi-spectral information about the Earth's surface (imagery, land cover, vegetation indices and so on), air-borne sensors for detailed imagery but also for laser scans of physical or man-made structures (LiDAR), and sensors near, on, or under the Earth's surface measuring anything from physical characteristics (pressure, temperature, humidity) and phenomena (wind, rain, earthquakes), to the tracking of animals, vehicles, and people. Large-scale networks of sensors have been in existence for several decades. Examples include the network of the World Meteorological Organization (Figure 1) and the Argos network of buoys measuring temperature and salinity of the world's oceans (Figure 2). What is novel is the web-enablement of these sensors and their networks so that individual sensors can be discovered, tasked, and accessed through web standards (sensor web), and that the networks can exchange information through interoperability arrangements.

Figure 1: Weather and Climate measuring network



(Source: GEO, 2007a)

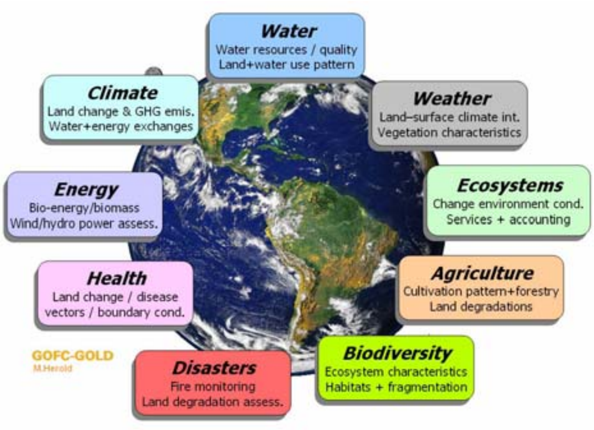
Figure 2: the ARGO Buoy Network



(Source: GEO, 2007a)

Linking existing systems and networks to achieve comprehensive, coordinated and sustained observations of the Earth system is the objective of the Global Earth Observation System of Systems (GEOSS). GEOSS is overseen by the Group on Earth Observations (GEO)[10], an intergovernmental organization at the ministerial level comprising of 73 nations, the European Commission, and 52 international organizations. A major role of GEOSS is to promote scientific connections between the observation systems that constitute the system of systems, and promote applications across nine societal benefit areas (Figure 3).

Figure 3: GEOSS nine Societal Benefit Areas



Source: GEO, 2007b

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[10] http://earthobservations.org/

The GEOSS 10-Year Implementation Plan[11] (2005-15) underscores the point that the success of GEOSS will depend on data and information providers accepting and implementing a set of interoperability arrangements, including technical specifications for collecting, processing, storing, and disseminating shared data, metadata, and products. GEOSS interoperability will be based on non-proprietary standards, with preference to formal international standards. The architectural design of GEOSS mirrors to a large extent that of the SDIs discussed in Section 2.1, with emphasis on metadata, catalogues, clearinghouses and portals, and registries of existing standards across different communities.

It is worth noting that a new breed of sensor networks, called wireless sensor networks (WSN), have demonstrated the potential to revolutionize the way we acquire geospatial data. Different from the traditional, large-size, complex and costly sensor stations, a WSN typically consists of miniature, battery-powered nodes with power-efficient CPUs, short-range radios and low-cost sensors[12]. The software that runs on the WSN nodes allows them to self-assemble into *ad-hoc* networks, such that the network can be easily deployed (e.g., sensors can be seeded from a low-flying airplane throughout hazardous areas) and data can be relayed across multiple hops and from long distances.

As discussed previously, networks of sensors are not new. What is new is that WSN changes sensor deployment strategies. WSN allows:

(1) High resolution spatial and temporal sensing: WSN's self-assembled *ad-hoc* network and the WSN nodes' low unit-price makes very large scale deployments economically feasible[13], and also enables long-term data collection at scales and resolutions that are difficult, if not impossible, to obtain otherwise;

(2) Pervasive and non-intrusive sensing: WSN nodes' miniature size allows them to be embedded in the physical world without disturbing the environment;

(3) Proactive sensing: WSN nodes are proactive and intelligent sensors rather than passive data collectors. With embedded processors and radios, WSN nodes can be programmed to share information with each other and modify their behavior based on collected data. WSN nodes are, in fact, miniature computers and have been projected to be the next computing class in 2010 (Bell, 2008).

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[11] http://earthobservations.org/documents/10-Year%20Implementation%20Plan.pdf

[12] For example, a typical WSN node can be Crossbow Inc.'s MICA2 motes, which incorporates an 8-bit, 7 Mhz processor, a radio with a range of about 500 feet, 4KB or RAM, and 128KB of program memory. (www.xbow.com)

[13] Prices of a WSN node have been dropping steadily since these devices were introduced. Projection from one vendor (www.dust-inc.com) suggests that the cost will drop to about $10 at mass production stage.

This new class of sensing platform will provide SDIs and GEOSS with an unprecedented volume of real-time geosensor data, along with high spatial and temporal resolution.

A set of developments within the category of geosensors is that of citizens as sensors, volunteering geographic information. Goodchild (2007) argues that there is a long tradition of non specialists contributing to the collection of scientific information such as the case of the Christmas Bird Count (http://www.audubon.org/bird/cbc) or the collection of weather information in the GLOBE programme (http://www.globe.gov) but that only recently the convergence of greater access to broadband connections, the availability of Global Positioning Systems at affordable prices, and more participative forms of interaction on the Web (Web 2.0) have enabled vast numbers of individuals to create and share geographic information. Platforms such as Google Maps and Microsoft Live Search Maps have made it possible to publish and make geographically searchable user-generated content to an unprecedented rate. Initiatives such as Wikimapia[14] and OpenStreetMap[15] show how organised volunteered information can challenge traditional data suppliers with good-quality products that are openly accessible to all. As observed by Goodchild, the potential of up to 6 billion human sensors to monitor the state of the environment, validate global models with local knowledge, and provide information that only humans can capture (e.g. emotions, and perceptions like fear of crime) is vast and has yet to be fully exploited. In general SDIs as currently designed and implemented do not handle well geosensor-based data (beyond remotely sensed imagery snapshots), which tend to arrive in real-time, are more continuous in the sense that changes over time can be considered at much higher frequency, and are available in much smaller packages than traditional georesources: entire images or maps.

2.4 Innovation in supporting technology

Digital Earths built today will be able to benefit from some very significant technology breakthroughs. Any Digital Earth will most likely be built using a technology stack comprising a lightweight client, a high speed computer network and a sophisticated server infrastructure. This type of computer system architecture in which data and processing resources are managed on remote

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[14] (http://www.wikimapia.org)
[15] (www.openstreetmap.org)

servers accessed over the Internet is now being referred to as 'cloud computing'[16] This is a type of 'utility' or service-based computing model.

The fact that today geobrowsers function at very high speeds while accessing, on-line, vast qualities of global-scale geodata is due in large part to advancements in the underlying technology. On the client side (local processing), the geobrowser today has access to many times more basic system memory than was available in desktop computers a decade ago. In its October 27, 1997 issue, *Electronic Times* told of home PCs being ready to make the jump from 32 MB to 64 MB of main memory, and for increases to be on the order of 20 MB annually through 2001. These estimates have been greatly surpassed, such that domestic laptop computers now boast up to 2-3 GB of main memory. More importantly the same has been true for graphics memory, key to making geobrowsers "fly" in real-time rather than as pre-recorded flights. While Keyhole co-founder Avi Bar-Zeev tells us (Crampton 2008) that at the time of Gore's speech PCs were capable of "fluidly drawing a 3D earth", we must remember that such capability was not in the hands of ordinary programmers. Today, however, all graphics programmers benefit from the evolution over the past decade of graphics hardware, from rendering thousands to several millions of polygons per second. Smooth graphic animation is also achieved by client (and server) caching of information that is progressively streamed over a network connect from a system of servers.

Given the vast quantities of information that are needed to represent Earth digitally (not to mention information licensing requirements) it is impractical for each user to maintain their own local copy of a Digital Earth. A more practical solution is to store the information of a collection of shared servers that can be accessed over a high-speed network connection, Although multiple protocols are available in theory, the major technology providers are rapidly converging on using Web protocols (especially http and XML).

On the server side, Google (and later Microsoft) boldly illustrated the speed accruing from distributing its index and its stored data across thousands of servers around the world. These servers cache copies of the most frequently used or viewed data, including map tiles. They are also capable of processing vast quantities of information in order to respond to client queries. These developments now make available to ordinary PC users what in Al Gore's speech was envisaged as requiring expensive and specialized head-mounted displays.

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[16] The term 'cloud' originates from the symbol used to represent the Internet on early conceptual diagrams of how distributed computer systems worked.

3. Strengths and weaknesses of current developments

The preceding section has provided a broad-brush overview of developments providing context for our vision of a Digital Earth as a framework to harmonise our efforts in the geospatial information realm, and to increase our collective understanding of the state of our planet and the interactions between physical and societal environments on it.

It is important to acknowledge that each set of initiatives introduced in Section 2 has its own characteristics in terms of leading actors, drivers, target audience, and implementation mechanism as summarized in Table 1. For the sake of clarity, GEOSS and volunteered geographic information (VGI) are treated separately in the table.

Table 1: Key features of recent developments

	Lead Actors	**Key Drivers**	**Main Target Audience**	**Implementation mechanism**
SDI	Public sector	Inform policy	Analysts in public sector	Legal framework (not always)
Geobrowsers	Private sector	Market share + Advertising Revenue	Mass market	Market + voluntary
GEOSS	Public sector	Inform policy	Scientists	Voluntary + political
VGI	Individuals/groups	Social networking	Society	Voluntary

As indicated in the Table, SDIs and GEOSS have many similarities in respect to leading actors, drivers, and primary target audiences. Both have a focus on data search, retrieval, and access, which then needs processing by experts in the different domains. Their appeal to non-expert users is therefore limited, until such time when many services are developed on top of these infrastructures to process the data and return information understandable and relevant to non-experts. Their basic architecture is also similar, and based on distributed nodes and systems that rely on metadata, catalogues, and a set of ancillary services to search, and retrieve the data. GEOSS emphasizes also dissemination services able to cater for different communities with varying level of access (e.g. GEONetcast services for data dissemination via satellite communication in developing countries).

There are some differences between SDIs and GEOSS, particularly in relation to implementation mechanism: whilst SDIs are by and large being developed within the bounds of legal and administrative jurisdictions which may avail themselves of legal tools to impose specifications and data sharing policies, GEOSS is entirely voluntary (although with strong political backing), and needs to balance the respect for existing systems, with their technical and data policy characteristics, with the need to develop agreed interoperability arrangements and data sharing principles to support the long term sustainability and use of earth observations. As progress is being made on interoperability at the technical level, greater attention is now been given to the data policy dimension, which is particularly challenging for the implications it may have on organizational arrangements and dependencies.

In addition to these similarities and differences, SDIs and GEOSS share a number of limitations in the components of their infrastructures and approach:

Metadata: useful to make visible the wealth of information resources already existing and to allow the opportunity for re-use. However, current standards-based approaches to metadata require considerable human input, and are difficult to maintain up-to-date. Moreover, they primarily represent the perspective of the data producer on the quality and utility of the data, and do not allow for users to express their measures of fitness-for-purpose. Also they are focused on datasets, not features themselves, and they do not adopt recent innovations in related fields of multimedia data exploitation, which embed a significant amount of metadata with the data themselves.

Catalogues: stores of searchable metadata reflecting a library metaphor. Separating the metadata from the data they refer to poses challenges of synchronization in the event of change. Searching across distributed catalogues is time consuming, and current OGC specifications are not tight enough to allow for unequivocal implementation, so that individual adapters may be required for each catalogue, minimising scaleability[17]. Multilingual search and retrieval are also very challenging and in need of further work.

Geoprocessing services: very few are available to process data into information relevant to different categories of users. The description of services in respect to processes, relevance, limitations, expected outcome, reliability, and trustworthiness needs significant additional work, as well as the chaining of services which is still at an early stage and requiring considerable expert input (Crosier et al., 2003). A promising development is the emergent interest in GEOSS for grid processing to support complex model processing, and countries

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[17] See http://inspire.jrc.it/reports/DistributedCatalogueServices_Report.pdf

that don't have adequate computer facilities. Geoprocessing services are offered (shared) by GEO members (same approach for large data repositories). This provides an interesting potential link with the activities taking place in e-science[18] and cyber-infrastructures[19], although the synergy between these activities, GEOSS, and SDI developments needs to be developed further.

Portals and view services: many geo-portals exist worldwide, providing entry points to SDIs (Maguire and Longley, 2005). Useful as they are, they often still display a 2-D cartographic background, and a GIS layered view of the world which makes them unattractive to non-experts and distant from the Digital Earth vision and the user experience of geobrowsers.

Data: even for expert users, the ability to integrate data from distributed sources (and disciplines) is hampered by the lack of explicit documentation of the semantic properties of the data and mechanisms to refer such properties to agreed semantic reference systems in a similar way as they would do when transforming data to a spatial or temporal reference system (Kuhn, 2003).

Time: current SDIs address relatively static data in time slices, similar to traditional GIS. As more and more dynamic data becomes available, through geosensors for example, better ways to integrate spatial and temporal data, analysis, and modeling are needed.

Model interoperability: GEOSS is aiming to link systems that often deal with n-dimensional data which are needed to gain a better understanding of the complex processes taking place in the Earth system, and to model future scenarios. Model and process interoperability across multiple disciplines takes the semantic reference system challenge one step further. Some initial research has been undertaken in the context of the GEOSS Interoperability Process Pilot Project (IP3) (Khalsa et al. 2008, 2007), and further work is expected in the coming years but there is little doubt that this is one area of major scientific challenge for the foreseeable future.

Policies: searching, finding, and accessing data and services require not only a technical infrastructure but also a policy one. Some international agreements and treaties exists in respect to Intellectual Property rights (WIPO Berne Copyright Convention 1976, and WIPO Copyright Treaty 1996), the environment and environmental information (e.g., Aarhus Convention, and Convention on Biodiversity), together with UN principles relating to Remote Sensing of Earth from Space (UNGA 1986). The extent to which further agreements are needed to address access and use of heterogeneous and distributed data sources can be

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[18] www.rcuk.ac.uk/escience/

[19] http://www.nsf.gov/dir/index.jsp?org=OCI

assessed by the fact that at the present time the OECD, GEOSS, and the European Commission are all engaged in developing principles and guidelines for data sharing, access and re-use (see for example OECD, 2008). Although addressing slightly different audiences, these efforts all need to address the balance between economic interests of data providers and member states with considerations of openness, equity, and access particularly in matters relating to environmental and human well being.

Equity: appropriate technology and policies to enable access to data and information are crucial but cannot go without the infrastructure to develop capacity, skills, and knowledge at the level of the individual, organization, and institution so that information can be turned in actionable empowerment. All too often the development of SDIs and related information infrastructure seems to underestimate the importance of investing also in the education and capacity-building programmes necessary for these infrastructures to support development and not widen the digital divide.

4. Overcoming the limitations

What can the current generation of SDIs and GEOSS learn from geobrowsers, social networking, and volunteered geographic information (VGI) to help overcome some of the limitations highlighted above? Clearly the success of geobrowsers with hundreds of millions of users demonstrates the power of the Digital Earth vision, and of simple and free applications (Crampton, 2008). Intuitive interfaces, speed in search and retrieval, and the use of imagery which is often more understandable than maps to non-expert users have contributed to the widespread use of these tools, and the popularization of geography as a way to organise information. They have created the informational and technical infrastructure, with hundreds of thousands of computers organised in server farms (the so-called “cloud computing” architectural style), upon which many other applications can be built, including VGI. Harvesting data and metadata and building centralised indexes overcomes existing limitations of distributed searches via catalogues. At the same time, what is technically achievable by single industries may not be politically acceptable if attempted by government organizations at national or international levels for perceived loss of sovereignty, ownership, and privacy. It is noticeable how individuals may be less concerned about giving away personal information to a private company than to a government organization (Economist, 2008a). Moreover, the development of large server farms begins to raise issues about their environmental footprint i.e. energy consumption (Economist, 2008b).

Whilst geobrowsers have democratized access to geographically organised information, their stated mass-market orientation means they are less concerned with scientific and policy domains. They therefore do not support an understanding of the current state of the Earth, changes over time, causes of change and relationships between physical phenomena and human activities. Data is generally not accessible, and the notions of a laboratory for multi-disciplinary science and a bridge between science and society are not amongst their objectives. This argues for the development of not one Digital Earth, but multiple interoperable ones, addressing different audiences but with the ability nevertheless to communicate, share, and learn from each other.

Social networking, Web 2.0, and VGI offer also enormous opportunities to develop SDIs for scientific and policy-support purposes which are yet to be exploited. As an example, some of the current limitations of metadata could be overcome with more participative methods of user classification and feedback, similarly to what is already common practice in commercial services such as Amazon or eBay. Equally, offering users information about what previous users have found interesting and useful may facilitate searching and retrieval beyond the current flat database structures of catalogues. The opportunity for GEOSS to include information provided by local communities about their environment should also be grasped in order to achieve its stated vision of realizing “a future wherein decisions and actions for the benefit of humankind are informed via coordinated, comprehensive and sustained Earth observations and information” (GEO, 2005). Not only are local communities the best source of knowledge about local conditions and changes, but their engagement in a shared framework would also address the equity, access, and empowerment issues highlighted above as one of the important limitations of current approaches. Clearly, there are also issues to be still fully addressed like the motivation people have to volunteer information, the process needed to assure the quality of the information provided, and appropriate technologies to enable people in every part of the world to participate regardless of their social, economic, and cultural contexts.

5. Towards the next-generation Digital Earth

How the Earth’s environment is changing, and what are the consequences for human civilization, are among the fundamental questions of our time. Sound scientific knowledge, and reliable and up-to-date environmental data and information, are necessary to address these questions and underpin the policies necessary to affect change. As indicated earlier significant progress is being made in the availability and quality of environmental and geographic information at our disposal, and in connecting information systems and new sources of data. The diffusion of SDIs, the efforts of GEOSS, and developments in industry and civil society have major contributions to make in answering these critical questions. Taken individually however, none of these developments can achieve the objective or get us to the vision of Digital Earth put forward more than 10 years ago. Now is the time to set a new vision of what can be achieved within the next 5-10 years, building on what is existing, bridging the gaps, and overcoming the limitations identified. Below are the initial elements of such a vision.

1. Not one Digital Earth, but multiple connected globes/infrastructures addressing the needs of different audiences: citizens, communities, policy-makers, scientists, educationalists.

   Each audience has a distinct set of needs for information about Earth and its future, so we anticipate that each would be accommodated by a specially designed Digital Earth. One might encourage members of the general public to contribute their own observations, while another would present only the most rigorously obtained scientific results. Each would be a *view*, however, of a single coordinated, distributed data resource. Different views would require different levels of detail, of geometry, imagery, attributes (semantics), etc.

2. Problem oriented: e.g. environment, health, societal benefit areas, and transparent on the impacts of technologies on the environment

   While it is important that specific problems be addressed in focused ways, Digital Earth should still clarify the interactions between problems and objectives – the difficulties of achieving one objective, such as reducing the costs of energy, with others such as impacts on the environment and food production.

3. Allowing search through time and space to find similar/analogue situations with real time data from both sensors and humans (different from what existing GIS can do, and different from adding analytical functions to a virtual globe)

   While there are strong affinities between the current generation of virtual globes and earlier GIS technology, it is clear that users expect virtual globes to answer a different kind of query, one that is less precise and quantitative, and more attuned to exploration and browsing. For example, one popular use of Google Earth is to search the globe for similar conditions – for example, to find areas that are as vulnerable to tsunamis as the coasts of the Indian Ocean.

4. Asking questions about change, identification of anomalies in space in both human and environmental domains (flag things that are not consistent with their surroundings in real time)

   One of the most compelling benefits of satellite images, maps, and virtual globes lies in their ability to provide context, by displaying information in its correct geographic position. The next generation of Digital Earth should allow for rapid search for geographic anomalies, that is, situations that are inconsistent with their geographic context, such as outbreaks of disease, biodiversity hotspots, or anomalous levels of air pollution.

5. Enabling access to data, information, services, and models as well as scenarios and forecasts: from simple queries to complex analyses across the environmental and social domains.

   One of the challenging issues today is to combine environmental modeling and forecasting with its socio-economic impacts. Traditional flood forecasting or mapping of natural hazards risk zones loose their value if their social impact is not assessed. Meanwhile such models have immediate economic consequences (e.g. property value reduction in the case of identified risk) and for this reasons both model reliability and appropriate communication tools (including visualization) are strongly required.

6. Supporting the visualization of abstract concepts and data types (e.g. low income, poor health, and semantics)

   Advances in dynamic visualization environments (see, for example, www.gapminder.org) show strong potential for decision support and increased understanding of global, complex, and abstract phenomena. Bringing these capabilities to the next generation Digital Earth will turn these into important tools for education, awareness-rainsing, and informed decision making. Different perspectives on phenomena like poverty or health and their indicators can now be made explicit through ontologies, and mappings between them have become possible.

7. Based on open access, and participation across multiple technological platforms, and media (e.g. text, voice and multi-media)

   The geoinfo community may have a great deal to learn from the wider multimedia community. For this to happen the emphasis on maps (fixed geometry plus labels) as central object of inquiry, study and navigation, must shift and dynamic elements must be incorporated. There is promising work already underway that integrates georeferenced moving video with other static geographic data sets.

8. Engaging, interactive, exploratory, and a laboratory for learning and for multi-disciplinary education and science.

   The notion of virtual collaboratories is a key feature of e-Science (Access grid20) to support the multidisciplinary exchange of knowledge across scientific teams dispersed at multiple locations. In other fields interactive learning tools, distance learning but also location-based games offer platforms and lessons that can be built upon to develop teaching, learning, and sharing environments for multiple audiences.

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[20] www.accessgrid.org/

6. Research needed to achieve the vision

1. Information integration (multi source and heterogeneous, multi-disciplinary, multi-temporal, multi-resolution, and multi-media, multi-lingual)

   Despite substantial progress, our ability to integrate geographic information from multiple sources is still quite limited. We need a better understanding of the statistical problems of integration across scales, the linguistic problems of integrating across languages, and the semantic problems of integrating across disciplines. This will require a substantial effort by a number of collaborating disciplines: computer science, information science, and the domain disciplines.

2. Space-time analysis and modelling (i.e. universal elements and language for dynamic modelling, algebra of space-time change)

   The next generation of Digital Earth should provide a powerful platform for simulating the human and physical processes that operate on the Earth's surface. While such models have been developed in many domains, they use a myriad of approaches that are impossible to couple or integrate. Fundamental research is needed to develop a comprehensive language for simulation, and the software components needed to make simulations easily interoperable across disciplinary boundaries.

3. Schemes for tiling the curved surface of the Earth and for use in data management, analysis, simulation, visualization

   Each of the current generation of virtual globes uses its own approach to structuring data. These systems are optimized for storage and display purposes, but have limitations for the analysis of global scale data and processes. Research on optimal structuring and indexing schemes has been under way for the past two decades, but we do not yet know how to design an optimal scheme that can support massive simulation of Earth-surface processes.

4. Intelligent descriptions (automatic, user driven) of data, services, processes, models, searching and filtering

   Good progress has been made on standardizing the description of data, through metadata and syntax standards. Still missing, however, are adequate standards for the description of models, processes, and services that can support search and the assessment of fitness for use.

5. Visualization of abstract concepts in space

   Transformations from lower level, physical observations through indicators defined on them, to abstract concepts like quality of life or vulnerability need to be modelled and implemented, to support visualization and reasoning. The wealth of data sources that can now be tied into Virtual Globes, together with advances in complex system modelling and semantic mappings, provide a richly equipped laboratory for domain and information scientists to enable new uses of Virtual Globes. Progressing from specific, well-defined case studies on well-defined scientific phenomena to more complex cases of socially defined and negotiated notions promises gradual, but significant progress.

6. Computational infrastructures to implement vision (architecture, data structures, indexing, interfaces)

   Advances in technology, information structuring, and organization of the IT infrastructure have already made it possible to come close to the vision of Digital Earth. The interoperability of multiple systems delivering data, information, and models in real-time from multiple sources, including passive sensors and humans, can increase by several orders of magnitude the quantity of information posing new challenges to deliver reliable, and timely quality information to multiple and diverse audiences through multiple access media including voice.

7. Trust, reputation and quality models for contributed information and services

   Progress from traditional provider perspectives on data quality to broader notions of fitness for use, trust, and reputation is already happening in the context of Volunteered Geographic Information. Models of spatio-temporal expertise can be developed and used in reasoning about the suitability of data and services for specific applications.

8. Governance models and collaborative frameworks (business, institutional, voluntary, communities of practice)

   The emergence of hybrid infrastructures can already be observed combining both voluntary and institutional data (e.g. using the Google platform). Without a mechanism to clearly distinguish the different nature of the data, users will be reluctant to take any formal decision (still recognising the value of non-institutional data). An important challenge is to build new models for reciprocal validation of data made available through collaborative frameworks (e.g. validation of precise quantitative comprehensive information about air quality collected through few professional measuring stations to be combined with air quality data collected through mobiles equipped with appropriate nanotechnologies measuring only a limited number of parameters). Communities of practice should be better engaged in Governmental decisions sharing their data and knowledge in an easier and effective manner

9. Data sharing and open access policies
   More systematic and comparable evidence is needed on the impact of different access policies on organizations and society in the face of multiple pressures on government budgets and increasing inter-organizational competition for funding. If such evidence was already in place, we would not still be facing tensions surrounding data access and sharing policies. More work is also needed on incentives and barriers to data sharing at individual, inter, and intra organizational levels.

10. Social and economic impacts of Digital Earth
    Appropriate theoretical and methodological frameworks to assess the social and economic impacts of geo-spatial information, and related infrastructures are still poorly developed but are urgently needed to justify the initial investment and the long-term sustainability of the infrastructure. The costs of not acting also need attention (in a similar vein as the Stern (2006) Review on Climate Change) at different scales from global, to regional, national, and local to inform appropriate funding and business models.

7. Next steps

This position paper is the outcome of a specialist meeting on Virtual Globes organised in June 2008 by the Vespucci Initiative for the Advancement of Geographic Information Science and the Joint Research Centre of the European Commission. It represents the views of the scientists coming from a range of disciplinary and professional experiences in the geographic, earth observation, and environmental fields. Over the coming eighteen months the paper will be presented to a wider range of stakeholders in these and related fields with a view to seek feedback as well as additional ideas both on the vision and the means to achieve it. At the end of this period we will report back on the feedback received, and monitor regularly the progress made on the Vespucci web site (www.vespucci.org).

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