www.sciencemag.org/content/353/6296/247/suppl/DC1

Supplementary Material for

Global trends in satellite-based emergency mapping

Stefan Voigt,* Fabio Giulio-Tonolo, Josh Lyons, Jan Kučera, Brenda Jones, Tobias Schneiderhan, Gabriel Platzeck, Kazuya Kaku, Manzul Kumar Hazarika, Lorant Czaran, Suju Li, Wendi Pedersen, Godstime Kadiri James, Catherine Proy, Denis Macharia Muthike, Jerome Bequignon, Debarati Guha-Sapir

*Corresponding author. Email: stefan.voigt@dlr.de

Published 15 July 2016, *Science* **353**, ppp (2016)
DOI: 10.1126/science.aad8728

This PDF file includes:

Materials and Methods

Gathering the numbers

In order to develop a comprehensive dataset, we gathered information from 15 years of activity from all major internationally relevant SEM mechanisms (see Table S1). 1,080 records were gathered from these sources and compiled into a database, reflecting and parameterizing major international SEM response efforts globally. The data were collected and input by professionals, who worked with the respective mechanisms at some time during the analysis period, and are familiar with SEM and the underlying methods and procedures. Data were collected from the archives of SEM mechanisms as well as relevant publicly accessible websites and reports, carefully reviewed and analyzed to extract the required information. Once completed, the records and parameters were cross-checked and examined for plausibility.

The 1080 records of SEM activations were collected from the CHARTER: n= 434; COPERNICUS: n= 163; NDRCC: n= 45; SENTINEL ASIA n=149 and UN: n= 289 covering a total number of 829 unique disaster events. 448 out of the 1080 records revealed some parallel and/or cooperative (shared) satellite mapping activities with other mechanisms. In 144 disaster cases the CHARTER provided satellite imagery to at least one of the SEM mechanisms under review for further analysis and mapping. These “shared” activations had to be controlled for in parts of the analysis, in order avoid double counting.

Statistical parameters from the Emergency Events Database (EM-DAT) (25) were added, as one of the authoritative global databases on natural disasters. Since there are often several SEM activations for single disaster events, EM-DAT was used for associating distinct SEM activations operated by different mechanisms into a unique reference scheme. This allowed a more accurate identification of the number of total disasters having SEM activations, assessment of levels of coordination, potential duplication and overall response rate, as well as patterns by region and over time. EM-DAT was also used to compare and evaluate SEM response patterns and rates against all disasters recorded. The EM-DAT database records the physical characteristics, human impacts such as deaths, affected, injured, and economic losses of each event that meets its inclusion criteria. This verifies each entry using a predefined set of disaster types and classifications established by an international scientific working group. We are fully aware of the fact that EM-DAT is likely to be incomplete in its records like most global datasets. However, it served well for the type of independent reference we needed to link the different sources of SEM data to and to perform a basic trend analysis, which would not be substantially influenced by a few possibly missing records. Such a reference was especially important as the different SEM mechanisms do not have standardized or common activation criteria as well as no sharply defined geographic reach.

The resulting SEM activation database has 83 attributes, including information such as location, dates of the disaster, and number of satellite images acquired and used, mapping products, involved mapping entities, and others. Historical records and all accessible parameters were retrieved for the time period 2000 - 2014. Not all parameters were avail-

able for all events, due to different levels of record keeping over the years. The database is therefore not inclusive of all parameters for all the events. However, best possible efforts were made to compile and reflect historical records on file as well as the domain experience of the authors involved in the study. The SEM database compiled for this study allows synoptic analysis and display of international SEM efforts, giving insight on how this domain developed.

Linking SEM and EM-DAT

In the 1080 SEM records, a subtotal of 211 unique disaster events was identified which did not match with a corresponding EM-DAT event. Combining these 211 unique SEM events with 6340 unique EM-DAT events resulted in a total number of 6551 unique disasters recorded for the period studied. We found two general trends by comparing SEM activations against natural disasters recorded in the Emergency Events Database (EM-DAT). The annual percentage of disasters with SEM activations grew from only 1% in 2000 to a peak of 27% in 2014. The overall mean average SEM response rate for EM-DAT events was almost 10% and a 13% response rate for all unique disasters recorded in the database. We also found an overall increase in the number of SEM activations over time for disaster events not recorded in EM-DAT. Of the 211 SEM unique events, over 54% occurred in the last five years (2010-2014). These events were not registered in EM-DAT because they were generally smaller-scale disasters with limited measurable human impact which were below EM-DAT qualification criteria: 10 or more people reported killed; 100 or more people reported affected; declaration of a state of emergency; call for international assistance. These SEM activations were more evenly distributed between developed and developing countries (43%-57%) than SEM activations for known EM-DAT events (20%-80%).

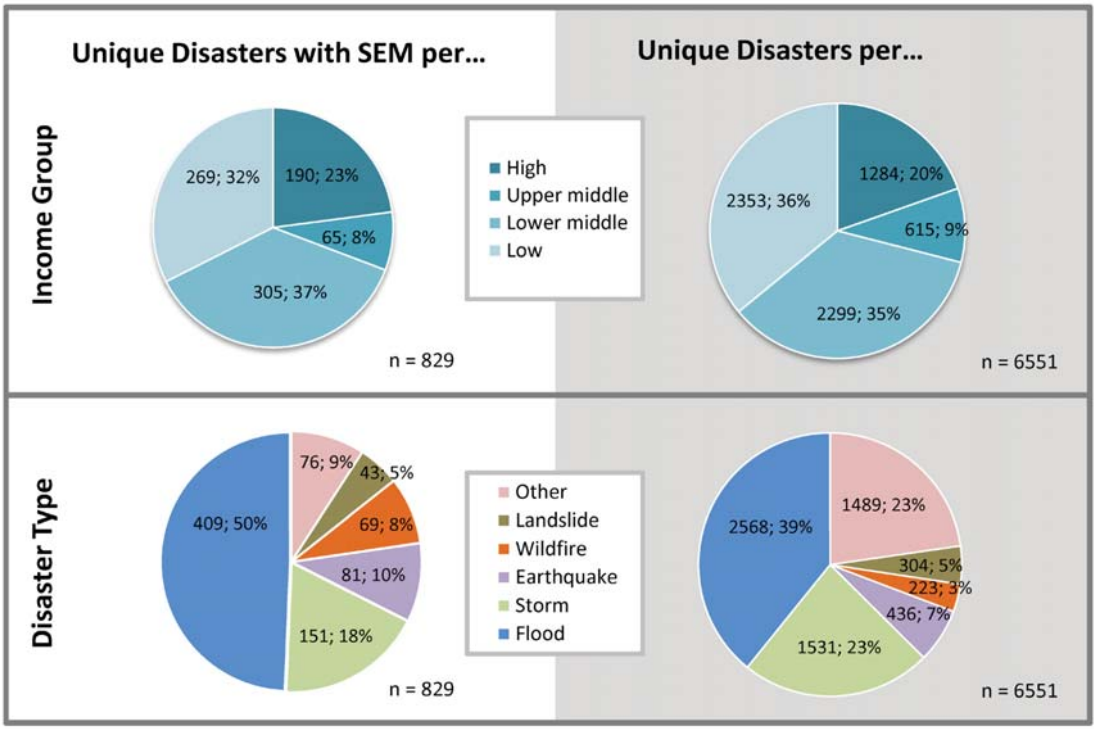
The increase in SEM activations over time for smaller disasters is consistent with expanding SEM mechanisms' capacity and response demand from civil protection and humanitarian agencies. The distribution of the SEM activations per country income group is similar to the disasters distribution recorded in the EM-DAT database (Fig. S1). This indicates that global international SEM activities are generally disaster and demand driven. With respect to disaster types, the distribution pattern of SEM activities closely follows that of the EM-DAT reference; showing positive bias towards floods, earthquakes and wildfires, with a negative bias for storms and "other" natural hazards/disasters. This reflects the ability of satellite mapping to pick up flood waters, severe earthquake damages and wildfire scars, better than e.g. storm damages. Among the disasters captured by SEM from 2000 to 2014, 50% are floods, storms (18%), earthquake (10%), wildfire (8%), landslide (5%), and others (9%).

Deriving spatial patterns and temporal trends in satellite response

For the purpose of deriving and visualizing global SEM patterns, the data were imported into a geospatial database. Available geographic coordinates of the centroids for each SEM record were obtained and verified for plausibility. SEM records, for which no coor-

dinates were available in the archives, were geocoded based on available information on the location of impacted areas. To bring the SEM patterns into the context of global population the patterns were synoptically displayed with the LandScan (27) data set (Fig 2). In order to study the temporal trends, we derived times series of SEM activations per mechanism per year and plotted the types of disasters to which SEM responded, and placed them in relation to the EM-DAT records (Fig. 1). To derive the SEM response times we controlled for shared activations between SEM mechanisms and excluded records with time stamps that implied non-rapid SEM responses (T > 1 week for satellite image or map generation), which resulted in a number of n = 414 records. The duration from activation of the SEM mechanism to providing the first post event map was 3.6 days on average for the full study period. In 11% (n=117) of the SEM activations the first post event satellite maps were made available on the day after the disaster. Furthermore it has to be considered that the request to mobilize SEM capacities often came days, sometimes even a week or more, after the onset of the disaster. Such delays clearly highlight the need to improve communication between the relief and SEM communities. However, more recently, disaster responses are substantially improved in overall SEM responsiveness, especially in map generation. Considering that some SEM mechanisms started to deliver preliminary post-event analyses three hours after satellite image availability, the main bottleneck remains still in the satellite tasking, re-programming and image generation, which on average still required a bit less than 2 days in 2014 for the rapid response cases.

Fig. S1.



SEM response rates by disaster type and income group: Number of unique disasters with SEM responses during 2000-2014 aggregated by country income group and disaster types (left) and number of total unique disaster events aggregated for the same categories (right).

Table S1.

SEM mechanisms reviewed for this study

SEM Mechanism	Background	Main Characteristics
CHARTER	International CHARTER Space and Major Disasters (**CHARTER**), active since 2000.	Global Network of mainly public satellite operating agencies, providing imagery and SEM services to authorized users on a best effort basis in cases of major natural or manmade disasters.
COPERNICUS	European COPERNICUS Emergency Management Service (**COPERNICUS**) including the phase when it was still called 'Global Monitoring for Environment and Security' (GMES), active since 2005.	SEM service fully funded and implemented by the European Commission (since 2005 based on R&D funding, since 2012 procured through public tenders and defined service levels). It supports SEM for disaster and humanitarian crises. It can be triggered by EU Member State civil protection agencies and several European Agencies. Mapping products are provided free of charge and generally full and open in access.
NDRCC	Satellite Mapping unit of the National Disaster Reduction Center of China (**NDRCC**), active since 2005.	National Chinese Agency and Capacity under the China National commission for Disaster Reduction providing domestic SEM services for major disaster situations.
SENTINEL ASIA	Space-based disaster management support system in the Asia-Pacific region (**SA**) under Asia-Pacific Regional Space Agency Forum (APRSAF), active since 2007 for SEM activities.	Initiative in the Asia-Pacific region established in 2005 as a voluntary collaboration between regional space agencies and disaster management agencies for humanitarian purposes. It now covers not only response phase with SEM services but also mitigation/preparedness phase with capacity building, early warning system for specific disasters using satellite-based data, and others.
UNITED NATIONS	United Nations Institute for Training and Research (UNITAR) Operational Satellite Applications Programme, UNOSAT, active since 2003, and other United Nations relevant mapping gathered on the UNOCHA humanitarian information platform Reliefweb, active since 2000, partially earlier (**UN**).	UNOSAT: project based SEM service, active mainly within parts of the UN, provided SEM support on ad hoc basis for major natural disaster situations and humanitarian emergencies with UN involvement. Reliefweb: a web based humanitarian information service operated by the United Nations Office for the Coordination of Humanitarian Affairs (OCHA). It hosts and collects relevant SEM products from various sources.

Table S2.

Top-5 ranking countries, for which SEM mechanisms were activated, n.b. NDRCC only activates for China.

Mechanism	Top-5 countries activated for (number of SEM activations 2000-2014)				
CHARTER	United States (23)	Indonesia (16)	China (16)	India (15)	Philippines/Pakistan(14)
SENTINEL ASIA	Indonesia (27)	Philippines (18)	Viet Nam (14)	Japan (11)	Thailand (8)
COPERNICUS	Italy (17)	France (9)	India (6)	Romania (6)	Bulgaria (6)
UNITED NATIONS	Pakistan (20)	Philippines (19)	India (12)	Bangladesh (11)	Mozambique (10)

References and Notes

1. United Nations, Space-based Information for Disaster Management and Emergency Response, UN-SPIDER Knowledge Portal, accessed 10 December 2015; www.un-spider.org.

2. O. M. Bello, Y. A. Aina, Satellite remote sensing as a tool in disaster management and sustainable development: Towards a synergistic approach. *Procedia Soc. Behav. Sci.* **120**, 365–373 (2014). doi:10.1016/j.sbspro.2014.02.114

3. United Nations Development Programme (UNDP), "Human Development Report" (UNDP, New York, USA, 2015).

4. Committee on Earth Observation Satellites, *Satellite Earth Observations in Support of Disaster Risk Reduction*, S. W. Ivan Petiteville *et al.*, Eds. (CEOS, 2015), pp. 84.

5. A. Aitsi-Selmi, V. Murray, C. Wannous, C. Dickinson, D. Johnston, A. Kawasaki, A.-S. Stevance, T. Yeung, Reflections on a science and technology agenda for 21st century disaster risk reduction. *Int. J. Disast. Risk Sci.* **7**, 1–29 (2016). doi:10.1007/s13753-016-0081-x

6. A. Ajmar, P. Boccardo, F. Disabato, F. Giulio Tonolo, Rapid mapping: Geomatics role and research opportunities. *Rendiconti Lincei* **26** (suppl. 1), 63 (2015). doi:10.1007/s12210-015-0410-9

7. S. Voigt, T. Kemper, T. Riedlinger, R. Kiefl, K. Scholte, H. Mehl, Satellite image analysis for disaster and crisis management support. *IEEE Trans. Geosci. Remote* **45**, 1520–1528 (2007). doi:10.1109/TGRS.2007.895830

8. P. Boccardo, F. Giulio Tonolo, in *Engineering Geology for Society and Territory* (Springer, 2015), vol. 5, chap. 17, pp. 7.

9. X. Tong, Z. Hong, S. Liu, X. Zhang, H. Xie, Z. Li, S. Yang, W. Wang, F. Bao, Building-damage detection using pre- and post-seismic high-resolution satellite stereo imagery: A case study of the May 2008 Wenchuan earthquake. *ISPRS J. Photogramm. Remote Sens.* **68**, 13–27 (2012). doi:10.1016/j.isprsjprs.2011.12.004

10. K. Duda, B. K. Jones, USGS remote sensing coordination for the 2010 Haiti earthquake. *Photogramm. Eng. Remote Sensing* **77**, 899–907 (2011). doi:10.14358/PERS.77.9.899

11. S. Voigt, T. Schneiderhan, A. Twele, M. Gähler, E. Stein, H. Mehl, Rapid damage assessment and situation mapping: Learning from the 2010 Haiti earthquake. *Photogramm. Eng. Remote Sensing* **77**, 923–931 (2011). doi:10.14358/PERS.77.9.923

12. International Working Group on Satellite-Based Emergency Mapping (IWG-SEM) Webpage, accesseded 10 February 2016; http://iwg-sem.org.

13. K. Gaurav, R. Sinha, P. K. Panda, The Indus flood of 2010 in Pakistan: A perspective analysis using remote sensing data. *Nat. Hazards* **59**, 1815–1826 (2011). doi:10.1007/s11069-011-9869-6

14. W. Bank, Pakistan Floods 2010—Preliminary damage and needs assessment, accessed 31 May 2016 (2010); www.gfdrr.org/sites/gfdrr/files/publication/Pakistan_DNA_0.pdf.

15. K. Kaku, N. Aso, F. Takiguchi, Space-based response to the 2011 Great East Japan earthquake: Lessons learnt from JAXA's support using earth observation satellites. *Int. J. Disast. Risk Reduct.* **12**, 134–153 (2015). doi:10.1016/j.ijdrr.2014.12.009

16. J. L. Bessis, J. Bequignon, A. Mahmood, The International Charter "Space and Major Disasters" initiative. *Acta Astronaut.* **54**, 183–190 (2004). doi:10.1016/S0094-5765(02)00297-7

17. A. Mahmood, J. L. Bessis, J. Bequignon, L. Lauritson, K. V. Venkatachary, An Overview of the International Charter 'Space and Major Disasters'. *Int. Geosci. Remote Sens.* **2**, 771–773 (2002).

18. B. K. Jones, T. S. Striker, A. Mahmood, G. R. Platzeck, in *Time-Sensitive Remote Sensing*, C. D. Lippitt *et al.*, Eds. (Springer Verlag, 2015), pp. 79–89.

19. Regulation (EU) No 377/2014 of the European Parliament and of the Council of the 3 April 2014 establishing the Copernicus Programme and repealing Regulation (EU) No 911/2010 (2014); available at http://copernicus.eu/sites/default/files/library/Regulation_377_2014_Copernicus_3April2014.pdf.

20. K. Kaku, A. Held, Sentinel Asia: A Space-based Disaster Management Support System in the Asia-Pacific Region. *Int. J. Disast. Risk Reduct.* **6**, 1–17 (2013). doi:10.1016/j.ijdrr.2013.08.004

21. D. Guha-Sapir, P. Hoyois, R. Below, "Annual Disaster Statistical Review 2014—The Numbers and Trends," [Center for Research on the Epidemiology of Disasters (CRED), 2015].

22. World Bank, Country Income Groups, accessed January 15, 2016; available at http://data.worldbank.org/news/new-country-classifications-2015.

23. Materials and methods are available as supplementary materials on *Science* Online.

24. Oak Ridge National Laboratory, LandScan Population Data 2010, accessed 5 December 2015; available at http://web.ornl.gov/sci/landscan.

25. J. E. Dobson, E. A. Bright, P. R. Coleman, B. L. Bhaduri, in *Remotely Sensed Cities*, V. Mesev, Ed. (Taylor & Francis, London, Great Britain, 2003), pp. 267–281.

26. I. Ayala *et al.*, "The Value of Geoinformation for Disaster and Risk Management (VALID)," (Joint Board of Geospatial Information Societies, 2013).

27. Organisation for Economic Co-operation and Development, *OECD Handbook on Measuring the Space Economy* (OECD Publishing, 2012).

28. M. Rodell, I. Velicogna, J. S. Famiglietti, Satellite-based estimates of groundwater depletion in India. *Nature* **460**, 999–1002 (2009). Medline doi:10.1038/nature08238

29. J. S. Famiglietti *et al.*, Watching water: From sky or stream? *Science* **349**, 2 (2015).

30. A. AghaKouchak, A. Farahmand, F. S. Melton, J. Teixeira, M. C. Anderson, B. D. Wardlow, C. R. Hain, Remote sensing of drought: Progress, challenges and opportunities. *Rev. Geophys.* **53**, 452–480 (2015). doi:10.1002/2014RG000456

31. A. A. Borsa, D. C. Agnew, D. R. Cayan, Ongoing drought-induced uplift in the western United States. *Science* **345**, 1587–1590 (2014). Medline doi:10.1126/science.1260279

32. F. Checchi, B. T. Stewart, J. J. Palmer, C. Grundy, Validity and feasibility of a satellite imagery-based method for rapid estimation of displaced populations. *Int. J. Health Geogr.* **12**, 4–12 (2013). Medline doi:10.1186/1476-072X-12-4

33. F. Rembold, C. Atzberger, I. Savin, O. Rojas, Review - Using Low Resolution Satellite Imagery for Yield Prediction and Yield Anomaly Detection. *Remote Sens.* **5**, 1704 (2013). 10.3390/rs50x000x doi:10.3390/rs5041704

34. C. Yang, J. H. Everitt, J. M. Bradford, Evaluating High Resolution SPOT5 Satellite Imagery to Estimate Crop Yield. *Precis. Agric.* **10**, 292–303 (2009). doi:10.1007/s11119-009-9120-6

35. R. Bailey, Managing famine risk—Linking early warning to early action, accessed 5 June 2016 (2013); available at www.chathamhouse.org/sites/files/chathamhouse/public/Research/Energy,%20Environment%20and%20Development/0413r_earlywarnings.pdf.

36. United Nations Office for the Coordination of Humanitarian Affairs, ReliefWeb—West Africa: Ebola Outbreak—Mar 2014, accessed 5 June 2016 (2014); http://reliefweb.int/disaster/ep-2014-000041-gin.

37. I. C. S. M. Disasters, Ebola Epidemic in West Africa, accessed 15 March 2016; www.disasterscharter.org/web/guest/activations/-/article/other-in-sierra-leone.

38. J. S. Kargel, G. J. Leonard, D. H. Shugar, U. K. Haritashya, A. Bevington, E. J. Fielding, K. Fujita, M. Geertsema, E. S. Miles, J. Steiner, E. Anderson, S. Bajracharya, G. W. Bawden, D. F. Breashears, A. Byers, B. Collins, M. R. Dhital, A. Donnellan, T. L. Evans, M. L. Geai, M. T. Glasscoe, D. Green, D. R. Gurung, R. Heijenk, A. Hilborn, K. Hudnut, C. Huyck, W. W. Immerzeel, J. Liming, R. Jibson, A. Kääb, N. R. Khanal, D. Kirschbaum, P. D. Kraaijenbrink, D. Lamsal, L. Shiyin, L. Mingyang, D. McKinney, N. K. Nahirnick, N. Zhuotong, S. Ojha, J. Olsenholler, T. H. Painter, M. Pleasants, K. C. Pratima, Q. I. Yuan, B. H. Raup, D. Regmi, D. R. Rounce, A. Sakai, S. Donghui, J. M. Shea, A. B. Shrestha, A. Shukla, D. Stumm, M. van der Kooij, K. Voss, W. Xin, B. Weihs, D. Wolfe, W. Lizong, Y. Xiaojun, M. R. Yoder, N. Young, Geomorphic and geologic controls of geohazards induced by Nepal's 2015 Gorkha earthquake. *Science* **351**, aac8353 (2016). Medline

39. United Nations, 41/65 Resolution Relating to Remote Sensing of the Earth from Space, accessed 10 February 2016; available at www.un.org/documents/ga/res/41/a41r065.htm.

40. International Working Group on Satellite-Based Emergency Mapping, *Emergency Mapping Guidelines* (2014); available at www.un-spider.org/sites/default/files/IWG_SEM_EmergencyMappingGuidelines_v1_Final.pdf.

41. A. S. Belward, J. O. Skøien, Who launched what, when and why; Trends in global land-cover observation capacity from civilian Earth observation satellites. *ISPRS J. Photogramm. Remote Sens.* **103**, 115–128 (2015). doi:10.1016/j.isprsjprs.2014.03.009

42. University of Twente, ITC's Database of Satellites and Sensors, accessed 15 January 2016; available at www.itc.nl/research/products/sensordb/AllSatellites.aspx.

43. European Space Agency, Earth Observation Portal, accessed 1 December 2015; https://directory.eoportal.org/web/eoportal/satellite-missions.

44. Committee on Earth Observation Satellites, The CEOS Database, accessed 20 December 2015; http://database.eohandbook.com/timeline/timeline.aspx.