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Micro-satellite Data: Measuring Impact from Space

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Demystifying Satellite Imagery

Satellites are mobile, remotely controlled communications systems that orbit the planet, capturing imagery and other data for transmission back to Earth. While satellites can provide relatively high-resolution imagery of the entire globe, historically they have been operated by government agencies and a small number of companies. The instruments themselves traditionally cost between $200 and 500 million dollars, and leverage billions of dollars of public sector investment in research, development, and maintenance.[1] Access to imagery has thus been available to a limited set of organizations, including government space agencies, research institutions, and corporations with the analytic capacity to use satellite data for business intelligence and decision-making.

In recent years, there has been a rapid trend towards small private organizations sending their own satellites into the sky. Because these are much smaller in size, have shorter life cycles, and much lower upfront costs (as little as $30,000), they are often referred to as *micro-satellites*. The idea is that, instead of spending millions of dollars to send a single large satellite into space, one can send a large number of micro-satellites into orbit, effectively increasing coverage of the Earth. These micro-satellites may offer less coverage of the earth, at lower spatial resolution. But they provide more frequent image capture, at much lower cost. This approach is revolutionizing the field, providing greater access to data than ever before.

Micro-satellite data holds particular promise for global development organizations—especially those involved in environmental conservation, natural resource management, human settlements and humanitarian response. It is also becoming a useful tool for poverty mapping. Yet this potential is not realized without substantial technical challenges. The intent of this review is to:

- Outline the possibilities and limitations of using micro-satellite imagery for the implementers of global development programs;
- Sketch the landscape of imagery providers, and help organizations understand which features to consider when comparing different satellite products;
- Highlight examples of successful applications of satellite data in social, economic, and environmental interventions; and
- Project future trends in the use of micro-satellite imagery for monitoring and evaluation.

Why satellites?

Many development programs collect data on implementation and outcomes by deploying teams of enumerators to interview participants, observe practices, and report on outputs. Satellite imagery can augment, and in some cases even replace, M&E data collected from traditional methods on the ground. It is widely and often freely available, and it can be used within days or weeks after acquisition. For some sources, there is historical data going back as early as the 1980s.

But because it can only capture information that is detectable from space, certain variables of interest to NGOs cannot be captured through satellite imagery. In practice, this means that it is usually better suited for analyses of environmental phenomena, such as drought or flood monitoring. In addition, as satellite imagery is not limited to the visible spectrum, it is possible to collect data on variables such as aerosol presence or vegetation, which are typically only accessible through specialized instruments on the ground.

Credible

Collect high quality data and accurately analyze the data.

Imagery from satellites, when accessed through public or well-established private providers, is generally resistant to tampering or fraud. It is highly consistent from one time period to another, enabling the tracking of outcomes over time.[2] Since data are often available freely on the internet, others can analyze and report on the same data set you might use, providing a basis for comparison and serving as a sort of cross-check.

However, it is difficult for novice users to assess the quality of a satellite-based spatial analysis. For example, when data from different spatial scales or different sources are combined (for example when geographic features from LandSat data, at 30 m resolution, are combined with aerial image data on roads, at 1 m precision), it is easy to introduce errors due to misalignment, correlations, or variation in instrument calibration. Yet combining multiple sources of data is often essential when conducting spatial analyses, since most measurements made by satellites are indirect. For example, crop yields are not directly measurable from space. Instead, we measure reflectance of light off vegetation; this requires a "ground truth" observation to translate reflectance into expected yield. These issues can be a major challenge in the credible use of satellite data by non-profit organizations. Even simple annotation of satellite data, by hand, can be prone to errors, since (like survey data) it requires human observation and data entry.

Actionable

Commit to act on the data you collect.

Satellite imagery is a highly visual form of information that can be easily understood by general audiences. The intuitive aspect of a map tends to have greater impact on perception or understanding than the same data displayed in a set of tables. Moreover, satellite imagery can easily be overlaid with specific geographic features, such as roads or energy plants, to further a visual point. The capacity to observe global-scale patterns also increases the ability to connect recurring phenomena across great distances, such as deforestation or overfishing. These features can enhance the usability of the data, and may facilitate more targeted action.

Timing is another advantage of satellite data. When processing is streamlined and automated, analyzed images can be available in days or even hours after an event, enabling rapid surveillance of a situation or population, such as a natural disaster or a humanitarian crisis. By reducing the time needed to access reliable information, satellite data can greatly improve response time and the targeting of interventions. This contrasts with field surveying, which is relatively slow to generate quality data, and thus has seen limited use in times of crisis.

Responsible

Ensure the benefits of data collection outweigh the costs.

Large numbers of satellite and micro-satellite data sets are accessible online, free or relatively inexpensive, and can often meet the primary needs of organizations. But costs of satellite imagery are driven upward by applications requiring extremely high-resolution imagery at frequent points of time; this can require "tasking" a satellite to collect custom data from specific locations. As most micro-satellite providers are technology start-ups that operate on case-by-case basis, it is always a good idea to contact a provider directly, to inquire about potential discount rates for non-profits (which might or might not be advertised online). It is also important to consider the cost of different data-gathering options. Field surveying can be labor intensive, slow to generate actionable information, and relatively expensive to implement. The collection and analysis of micro-satellite data, once set up, can be largely automated and relatively cheap to operate.

One of the main advantages of satellite imagery is that it is not limited to any geographical boundaries. Although satellites are often tasked to focus on particular areas of the earth, it is technically possible to observe the entire earth over time. This can be particularly useful in places that are physically hard to access, such as dense forests, conflict zones, or areas hit by natural disasters. It can also help to overcome the reluctance of certain governments or civil groups to allow organizations to operate within their territories. Even in less extreme cases, the study of highly remote areas can make overland travel prohibitively expensive for a team of enumerators, but relatively cheap for users of satellite data.

Transportable
Collect data that generate knowledge for other programs.

Satellite data can generate two very transportable types of knowledge: 1) processed maps, which are useful for program planning and monitoring; and 2) protocols for data analysis. An organization's investment in collecting and analyzing satellite data often results in location-specific maps of features that may be of interest to others. An NGO may need to map forest cover overlaid with human settlements across a stretch of central Africa, and then make these maps available to others.

But just as important, the protocols for analysis of a satellite data (for example, the process used to estimate farmers' crop yields from space) may be reusable. These protocols are often developed by combining satellite data with "ground truth" information, such as surveys, photographs, or other direct on-the-ground observations. Once the up-front costs of designing the protocol have been covered, the method becomes available to others. In this sense, satellite data is highly transportable: methods developed using data from one region of the world, or for one application, may be reusable in new contexts. This allows advances in image processing to be applied across program sites or time periods.

Practical Considerations

Classification

There are two methods to extract data from satellite imagery (Table 1). *Manual* (or "by-hand") *classification* refers to individuals identifying features of interest in the images without the aid of computational algorithms. This is the most common and also the most accurate form of analysis, since human minds (thus far) outperform the best-trained algorithms. However, manual classification suffers from subjectivity bias, and can be time-consuming when dealing with high volumes of imagery. Most NGOs prefer this technique for its simplicity and precision. An example of manual classification is the examination of damaged building or impact craters to identify evidence of human rights violation in war-affected areas.

In contrast, *automated classification* relies on computer algorithms for image analysis. It is also referred to as *machine learning* since the algorithms are "trained" to analyze the imagery automatically, based on a small subset of images that has been manually classified beforehand. Today's algorithms are relatively good at identifying simple aspects of the imagery, such as colors or shapes. The main advantages of this approach are the subsequent savings in time and cost, after the initial system has been set up. Yet few NGOs currently use this technique, due to limited data engineering expertise and computer processing capacities (though tools such as Google Earth Engine are significantly lowering barriers to adoption). An example of automated classification is the analysis of crop yields from the sky, where satellite data are calibrated using on-the-ground measurements of a small plot of land[3]. Once the framework has been set up, the algorithm can be used to quickly and accurately estimate vegetative vigor for the rest of the imagery.

Table 1. Methods for Analyzing Micro-Satellite Data

Type	**Manual Classification**	**Automatic classification**
Procedure	Humans label imagery by hand.	Humans train a computer algorithm to label imagery automatically.
Suitable for	Complex scenes, small data sets, large set of possible labels.	Simple scenes, large data sets, limited set of possible labels to apply.
Level of expertise required	Low to medium.	High.
Cost	Low fixed cost, medium marginal cost (mostly labor).	High fixed cost, low marginal cost (mostly computation time).

Resolution

The quality of satellite data is limited by the resolution capabilities of the remote sensors charged to take the images from the satellites. For instance, a 30-meter resolution means that a single pixel represents a 30m x 30m square of land. At that resolution, vehicles are not observable, although large houses or settlements are. Over the past years, advancements in satellite technology have significantly improved available resolutions, with leading-edge imagery now at 0.5m-resolution or less. At this level, vehicles and sometimes individuals can be captured.

Yet higher-resolution imagery often creates challenges for organizations in terms of data analysis, both with regards to the expertise required and the computer time necessary for processing. The latter is simply a matter of data density: even at 30m resolution, an uncompressed image of San Francisco would require roughly four million pixels of data. While most NGOs might not possess the budget or data science expertise to process high-resolution satellite data, organizations such as Google have recently sought to fill this need by sharing hardware and software resources with interested partners.

Access

The extent of available satellite imagery has steadily increased since its inception in the 1970s. See Table A1 in the Appendix for a non-exhaustive list of the more popular types of imagery, both from free and commercial sources.

For cases where only low-to-medium resolution is required, imagery can usually be downloaded for free.

- **USGS Earth Explorer** (http://earthexplorer.usgs.gov/)
  USGS Earth Explorer is a large, accessible repository of a large number of freely-available satellite imagery data sources. Users can select the region of interest and download images from multiple satellites and time frames with relative ease. Of note, MODIS and Landsat imagery sets are both available from Earth Explorer. This is a good starting point for any initial foray into the use of satellite imagery.
- **Google Earth Engine** (https://earthengine.google.org/)
  Google Earth Engine is a distributed processing platform for satellite data. "Google Earth Engine brings together the world's satellite imagery — trillions of scientific measurements dating back over 40 years — and makes it available online with tools for scientists, independent researchers, and nations to mine this massive warehouse of data to detect changes, map trends and quantify differences on the Earth's surface." Earth Engine consists of both a data catalog (in open beta, as of November 2014) and an API (in closed beta, as of November 2014). Researchers can access numerous freely-available datasets in one place through the catalog, and perform image analysis in either Javascript or Python through the API.

Organizations with a non-profit or academic status are also often eligible for free or discounted access to otherwise costly sources of imagery. Before purchasing any imagery online, NGOs should always contact providers directly and request information on special pricing or grant options that might be available (even if not advertised). Several commercial providers have specific programs designed for this purpose.

- **Skybox for Good** (http://www.skybox.com/blog/introducing-skybox-for-good)
  Announced in October 2014, the Skybox for Good program will "contribute fresh satellite imagery to projects that save lives, protect the environment, promote education, and positively impact humanity." Skybox uses micro-satellites to produce very high-resolution imagery.
- **DigitalGlobe Foundation Grants** (http://www.digitalglobefoundation.org/application-process)
  DigitalGlobe has imagery grants available for faculty or students at universities.
- **Google Earth Outreach** (https://www.google.com/earth/outreach/index.html)
  Google Earth Outreach provides grants to non-profit organizations to use Google Earth Pro and other tools. Satellite imagery is accessible through Google Earth Pro, though not to the same extent as in Google Earth Engine. However, Google Earth Pro may be better suited for organizations simply looking to overlay other types of spatial data on satellite imagery.
- **UNITAR's Operational Satellite Applications Programme** (http://www.unitar.org/unosat/)
  UNITAR's Operational Satellite Applications Programme (UNOSAT) is a "technology-intensive program delivering imagery analysis and satellite solutions to relief and development

organizations within and outside the UN system to help make a difference in critical areas such as humanitarian relief, human security, strategic territorial and development planning."

- **Development Seed – Landsat API** (http://www.developmentseed.org)
  Development Seed has made available a command-line utility designed to facilitate searching, downloading, and processing Landsat Imagery. More information is available below.

Analytic Support
Increasingly, companies are directly analyzing satellite imagery and offering actionable insights or intelligence that can be readily applied by users. Many of these firms are start-up companies and include:

- **Orbital Insight** (http://orbitalinsight.com)
- **Spaceknow Inc.** (http://spaceknow.com)
- **Remote Sensing Metrics** (https://www.rsmetrics.com/)
- **OmniEarth** (http://www.omniearth.net/)
  DataKind (http://www.datakind.org/)

Privacy
Satellites image the world at coarse resolutions that do not typically allow for recognition of individuals, and they tend to image structures and features that are themselves publicly viewable. Nevertheless, when combined with survey data or other sources of information, satellite images can be used to identify individual households. This will require the continued protection of individual or household level data that is geo-tagged or otherwise identifiable by location.

There are ongoing debates about how the increasing spatial and temporal resolution of satellite imagery will affect privacy protections. Public access to imagery holds the promise to democratize this data stream, ensuring that civil society and public advocacy groups have the opportunity to analyze and use information from satellites alongside governments and corporations.

Future Prospects
Two main trends are currently developing in the satellite imagery industry: the increasing availability of very high-resolution satellite imagery, and the development of analysis platforms that outsource processing-intensive image analysis tasks to distributed computing.

Skybox (now owned by Google), Planet Labs, UrtheCast and other start-ups have recently entered the satellite imagery market with promises of low-cost, high-volume satellite data; established commercial competitors such as GeoEye, DigitalGlobe, RapidEye, and Spot have also joined the movement. As these organizations jockey for market shares, the costs of high-resolution imagery is likely to fall dramatically in the coming years. In addition, these companies have shown strong interest in partnering with NGOs and university researchers by providing imagery for free or at reduced cost. The financial burden traditionally associated with the acquisition and analysis of micro-satellite data is thus likely to decrease even further for non-profits in the future.

The opportunities provided by increasingly higher-resolution satellite images are linked with a significant challenge for data analysis—pushing the limits on bandwidth, storage, compute power, and statistical expertise of most organizations. To address these issues, technology companies are developing new tools to perform image processing on distributed computing platforms. An example of such a tool is Google Earth Engine, which provides access to both the imagery and the platform to analyze it. Currently in invite-only beta testing, Google Earth Engine is expected to launch publicly soon, while other competing platforms are also likely to emerge. This is good news for NGOs, as these companies has expressed a strong desire to partner with socially-minded organizations in developing their products.

There remains a great deal of untapped potential for the use of micro-satellite data in social, economic, and environmental interventions. Academic researchers are exploring a variety of new applications, yielding high prospects for NGOs that might not find clear pathways for the integration of these data into their monitoring and evaluation activities. These include spatially integrated social science[4], urban extent,[5] night-time lights,[6,7] crop yield gaps,[8] malaria early warning,[9] roads and deforestation,[10] land use change,[11,12] and natural disasters.[13,14]

And while the statistical methods used to analyze satellite data can be complex (particularly for indirect measurement of variables like crop yields or poverty levels), satellite imagery remains the best studied of all remote sensing data. Drones and other low-flying sensing devices (like LiDAR) are becoming increasingly available to end-users, but they have additional problems with tracing and reproducing flight paths. This adds a layer of complexity when interpreting the results of data collected with these technologies.

Case Studies

Agriculture

Healing Hands International (http://www.hhi.org/) (http://www.emergencymgmt.com/disaster/Satellite-Imagery-Helps-Plan.html)
Healing Hands International has used DigitalGlobe imagery to conduct needs assessments and evaluate potential impact of interventions before visiting possible locations for building irrigation systems or training farmers in use of fertilizers.

Cash Transfers

GiveDirectly (https://www.givedirectly.org/) (http://www.datakind.org/blog/using-satellite-images-to-understand-poverty/)
Leaning on a large body of scientific literature suggesting the benefits of unconditional cash transfers, GiveDirectly offers donations directly to low-income households in Kenya and Uganda. In partnership with Datakind, the organization used satellite imagery to classify the types of building coverings of potential recipients. Looking at the ratio of thatch-to-iron roofs in specific communities, GiveDirectly was able to identify neediest households to receive the donations. Although the analysis was done manually, the organization is currently developing a machine-learning algorithm to automate the task.

Crisis Mapping

The HALO trust (http://www.halotrust.org/)
(https://www.google.com/earth/outreach/stories/halo.html)
The HALO trust, an organization devoted to the clearance of landmines, uses satellite imagery within Google Earth Pro to determine landmines locations based on agricultural cultivation.

Imagery to the crowd (https://hiu.state.gov/ittc/ittc.aspx)
Imagery to the crowd (ITTC) is a project conducted by the Humanitarian Information Unit within the US State Department with the objective of crowd-sourcing satellite imagery analysis to the public. Users around the world can access the platform to classify high-resolution data in areas vulnerable to humanitarian crises where detailed data is not available. One example is the digitalization of building footprints in Kathmandu Valley to assess the risk of earthquakes in the region.

Deforestation

Global Forest Watch (http://www.globalforestwatch.org/)
Global Forest Watch (GFW) is a "dynamic online forest monitoring and alert system" created by the World Resources Institute and partners. GFW uses a variety of satellite imagery, most notably Landsat 7 and MODIS, to generate maps of both present and historical deforestation by looking at changes in vegetation indices over time. Notably, GFW makes use of Google Earth Engine to conduct most imagery acquisition and analysis. This allows ongoing monitoring via an automated image classification process.

Imazon (http://www.imazon.org.br/)
Imazon is a Brazilian organization that monitors deforestation using satellite data. Their system, SAD, uses MODIS satellite data to measure monthly rates of deforestation in the Amazon. Like Global Forest Watch, they have recently begun to use Google Earth Engine to acquire and analyze imagery rather than performing it all in-house.

Fisheries

Global Fishing Watch (http://globalfishingwatch.org/)
Global Fishing Watch is the product of a technology partnership between SkyTruth, Oceana, and Google that is designed to show all of the trackable fishing activity in the world's oceans, thereby helping marine conservation organizations to more effectively monitor illegal fishing activities.

Human Rights

Satellite Sentinel Project (http://www.satsentinel.org/)
The Satellite Sentinel Project (SSP) partners with DigitalGlobe, a commercial satellite imagery provider, to monitor human rights abuses in Sudan and South Sudan. DigitalGlobe satellites passing over the area provide relevant imagery to SSP and DigitalGlobe analysts, who search the imagery for "possible threats to civilians, detect bombed and razed villages, or note other evidence of pending mass violence."

AAAS Geospatial Technologies and Human Rights Project (http://www.aaas.org/content/high-resolution-satellite-imagery-and-conflict-eastern-burma-executive-summary)
The American Association for the Advancement of Science (AAAS) Geospatial Technologies and Human Rights Project analyzed satellite images of the Thai-Burmese (from GeoEye and DigitalGlobe) to corroborate reports of human rights violations in the area. Using manual classification, the research team compared before-and-after images of reported attack locations, revealing widespread internal displacements during the conflict in the region.

Human Rights Watch (http://www.hrw.org/news/2008/08/27/georgia-satellite-images-show-destruction-ethnic-attacks) (http://www.hrw.org/news/2008/06/12/ethiopia-army-commits-executions-torture-and-rape-ogaden)
Human Rights Watch (HRW) has used UNOSAT imagery to augment on-the-ground observations of looting, burning, damaged building, impact craters in war-affected areas such as Ethiopia, Somalia, Georgia, Sudan, and Syria. Using manual analysis, the analysis of the imagery has helped reinforced evidence of human rights abuses in these regions.

Migration

UNHCR (http://www.unhcr.org) (http://www.unhcr.org/4ca602a66.html)
The United Nations High Commissioner for Refugees has used satellite imagery to monitor the movement of internally displaced persons (IDPs) from Mogadishu to other areas of Somalia. According to a recent report, over 400,000 people have been displaced into the Afgooye corridor since fighting began in 2007. Researchers were able to produce this number by counting the number of different kinds of shelters present in the corridor and summing the product of the number of each type of shelter with its expected total occupancy.

Conclusion

Access to satellite imagery has largely democratized over the past couple of years. There are now a large number of companies providing high-resolution images at affordable rates (sometimes even free of charge). Satellite imagery can be used to monitor virtually anything visible from space. Unlike most other data collection methods, it is does not require any physical interaction with subjects or elements of interest, as the data is collected remotely from sensors placed on satellites orbiting the planet. Thereby, organizations can often access information that was traditionally challenging to gather because of geographical constraints, security risks, or crisis situations.

Once the process for collecting the imagery is set up, access to the data can be extremely fast, and the analysis can be largely automated through the use of machine-learning algorithms. The cost of dealing with micro-satellite data mostly depends on the type of imagery necessary to identify the elements of interests to the organization. The higher the resolution, the higher the need for computer power and data science expertise in-house. Most satellite imagery providers have shown a great deal of interest in partnering with socially-minded organizations, and it is thus highly encouraged to contact potential providers to inquire about discounted rates before purchasing anything online.

The list of NGOs relying on satellite data as part of their M&E operations is growing rapidly, spreading across sectors as diverse as agriculture, deforestation, crisis mapping, and human rights protection. Yet there remains a great deal of untapped potential for further applications. Successfully leveraging micro-satellite data in an organization does raise a number of challenges (mostly IT infrastructure and staff expertise), yet pay-offs can be huge.

Organizations should consider the whole range of data sourcing alternatives available to them, and determine which combination will allow them to access variables of interest for program tracking or impact measurement in the most efficient manner. Micro-satellite imagery, when seen as a complement of other methods and not as a substitute, can often help organizations better monitor their activities and report on program outcomes. As the cost of acquiring imagery continues to decrease and technology companies develop new tools to overcome image processing challenges, it is expected that NGOs will see an increasing number of opportunities for using satellite data in the years to come.

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References

[1] Weber, Robert A., and Kevin M. O'Connell. "Alternative futures: United States commercial satellite imagery in 2020." *Department of Commercial, Commercial Remote Sensing Regulatory Affairs* (2011).

[2] Kennedy, Robert E et al. 2009. *Remote sensing change detection tools for natural resource managers: Understanding concepts and tradeoffs in the design of landscape monitoring projects.* Remote Sensing of Environment. 113(7): 1382–1396.

[3] Lobell, David B. 2013. "The Use of Satellite Data for Crop Yield Gap Analysis." *Field Crops Research*, Crop Yield Gap Analysis – Rationale, Methods and Applications, 143 (March): 56–64. doi:10.1016/j.fcr.2012.08.008.

[4] Goodchild, Michael F., and Donald G.s Janelle. 2004. *Spatially Integrated Social Science*. Vol. 5. Oxford University Press New York. https://www.msu.edu/~moranef/documents/04-01_InferringtheBehavior.pdf.

[5] Schneider, Annemarie, Mark A. Friedl, and David Potere. "A new map of global urban extent from MODIS satellite data." *Environmental Research Letters* 4, no. 4 (2009): 044003

[6] Henderson, J. Vernon, Adam Storeygard, and David N. Weil. 2009. *Measuring Economic Growth from Outer Space*. Working Paper 15199. National Bureau of Economic Research. http://www.nber.org/papers/w15199.

[7] Chen, Xi, and William D. Nordhaus. 2011. "Using Luminosity Data as a Proxy for Economic Statistics." *Proceedings of the National Academy of Sciences* 108 (21): 8589–94. doi:10.1073/pnas.1017031108.

[8] Lobell, David B.

[9] Rogers, David J., Sarah E. Randolph, Robert W. Snow, and Simon I. Hay. 2002. "Satellite Imagery in the Study and Forecast of Malaria." *Nature* 415 (6872): 710–15. doi:10.1038/415710a.

[10] Nelson, Gerald C., and Daniel Hellerstein. 1997. "Do Roads Cause Deforestation? Using Satellite Images in Econometric Analysis of Land Use." *American Journal of Agricultural Economics* 79 (1): 80–88. doi:10.2307/1243944.

[11] Muller, Daniel, and Manfred Zeller. 2002. "Land Use Dynamics in the Central Highlands of Vietnam: A Spatial Model Combining Village Survey Data with Satellite Imagery Interpretation." *Agricultural Economics* 27 (3): 333–54. doi:10.1111/j.1574-0862.2002.tb00124.x.

[12] Seto, Karen C., and Robert K. Kaufmann. 2003. "Modeling the Drivers of Urban Land Use Change in the Pearl River Delta, China: Integrating Remote Sensing with Socioeconomic Data." *Land Economics* 79 (1): 106–21. doi:10.3368/le.79.1.106.

[13] Jina, Amir, Raymond Guiteras, and A. Mushfiq Mobarak. "The Long-Term Impacts of Flooding on Human Capital Formation in Bangladesh." *Working Paper*. http://blogs.cuit.columbia.edu/asj2122/research/.

[14] Tralli, David M., Ronald G. Blom, Victor Zlotnicki, Andrea Donnellan, and Diane L. Evans. 2005. "Satellite Remote Sensing of Earthquake, Volcano, Flood, Landslide and Coastal Inundation Hazards." *ISPRS Journal of Photogrammetry and Remote Sensing*, Remote Sensing and Geospatial Information for Natural Hazards Characterization, 59 (4): 185–98. doi:10.1016/j.isprsjprs.2005.02.002.

Table A1. Popular Types of Satellite Imagery

Type of imagery	Provider	Resolution (m)	Temporal coverage (frequency)	Temporal span	Cost	Mostly suitable for
MODIS	NASA	500	1-2 days	1999-present	Free	Vegetation monitoring, atmospheric conditions
Landsat 1-8	NASA	30 (varies)	16 days	1972-present	Free	Urban extant, land use change, vegetation monitoring, atmospheric conditions
ASTER (infrared bands)	NASA, METI, ERSDAC	30	16 days	1999-present	Free in the US	Urban extant, land use change, vegetation monitoring, atmospheric conditions
CBERS 1-2	China, Brazil	20	26 days	1999-present	Free	Urban extant, land use change, vegetation monitoring, atmospheric conditions
ICESAT/GLAS (LIDAR; elevation data only)	NSDIC	60	91 days	2003-2009	Free	Ice, cloud, and land elevation
Skybox	Skybox Imaging, Google	0.9	N/A	2014-present	Case-by-case	High-detail agricultural monitoring, urban-area land use, refugee movements, commodity storage, natural disasters, houses, roads, automobiles, large groups of people
Planet Labs	Planet Labs	4	N/A	2014-present	Case-by-case	High-detail agricultural monitoring, urban-area land use, refugee movements, commodity storage, natural disasters, houses, roads
GeoEye-1	DigitalGlobe	1.65	8.3 days	2008-present	Varies; Around $25 per km^2; Grants available	High-detail agricultural monitoring, urban-area land use, refugee movements, commodity storage, natural disasters houses, roads, automobiles, large groups of people

IKONOS	DigitalGlobe	3.2	3 days	1999-present	Varies; Around $25 per km^2; Grants available	High-detail agricultural monitoring, urban-area land use, refugee movements, commodity storage, natural disasters houses
Worldview 1-3	DigitalGlobe	1.24	1.7 days	2007-Present	Varies; Around $25 per km^2; Grants available	High-detail agricultural monitoring, urban-area land use, refugee movements, commodity storage, natural disasters, houses, roads, automobiles, large groups of people
Quickbird	DigitalGlobe	2.62	2.5-5.6 days	2001-present	Varies; Around $25 per km^2; Grants available	High-detail agricultural monitoring, urban-area land use, refugee movements, commodity storage, natural disasters, houses, roads, automobiles, large groups of people
RapidEye	Blackbridge	6.5	5.5 days	2009-present	Area dependent	High-detail agricultural monitoring, urban-area land use, refugee movements, commodity storage, natural disasters, houses
SPOT 1-6	Airbus	1.5 (varies)	daily	1986-present	Varies; Around $5,000 per scene (60km x 60km)	High-detail agricultural monitoring, urban-area land use, refugee movements, commodity storage, natural disasters, houses, roads, automobiles, large groups of people
Pleiades 1A-1B	Airbus	2	26 days (taskable to daily)	2011-present	Varies; Around $20 per km^2	High-detail agricultural monitoring, urban-area land use, refugee movements, commodity storage, natural disasters, houses, roads, automobiles, large groups of people

Notes: Many satellites have a variety of resolutions and temporal coverages available. Those listed above corresponds to the most recent multi-spectral resolution currently available. Most satellites also have a panchromatic (black and white) band available at a higher resolution, which can be used to sharpen the image. Some of the entries above represent multiple satellites in the same family, e.g. Landsat 1-8. In general, these satellites serve the same purpose, but later satellites are often more advanced, featuring better resolutions and temporal coverage than their predecessors. Price quotes are approximate. Most consumers of satellite imagery arrange to purchase large quantities through a negotiated contract price below that listed online. Non-profit consumers should request a discount directly from the imagery provider. This information was collected from provider websites and http://carpe.umd.edu/geospatial/satellite_imagery_resources.php.

Appendices

While not technically satellite imagery, aerial and drone imagery can both serve a similar purpose: taking pictures of earth from higher elevation in order to better understand the situation on the ground. Both are taken from substantially lower altitudes than satellite imagery.

Aerial Photography (http://eros.usgs.gov/aerial-photography)
Aerial photography, or imagery, is considerably older than satellite imagery. Aerial photography is generally conducted using airplanes, although other airborne vehicles have been used as well. Because it lacks the consistency of satellite imagery, aerial photography is less useful for automated image classification, but can often provide much higher-resolution images than are typically available from satellite imagery and can be very useful where manual classification is employed. The US Geological Survey maintains a large list of available aerial photography.

Drone Imagery (http://dronemapper.com/sample_data)
Drone imagery is a subset of aerial photography, where the picture-taking object is an unmanned drone aircraft. Drone imagery can be used to provide extremely high quality imagery of a small area, often using many hundreds of images to reconstruct a full 3D scene of the surface in question. Like most aerial imagery, drone imagery lacks the consistency of satellite imagery but can achieve considerably higher resolutions over a small area at fairly low cost.