# Resolution in Space-based Earth Observation and Recent Technological Trends

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**Abstract**

Earth observation and monitoring is a critical task for many applications nowadays. The performance of a remote sensing system can be measured in terms of its resolution, the ability to distinguish details in a measurement. This paper introduces the four main types of resolution: spatial, radiometric, spectral, and temporal resolution, and discusses technological trends through concrete operational examples.

Space-based Earth observation is a very active field in space missions. Satellites orbiting our planet can provide an unmatched capability of monitoring, which is useful for a wide range of scientific and applicative tasks. In this context, the technologies for remote sensing that are most involved are passive and active sensors in the electromagnetic spectrum. In particular, radar and passive light detectors are used daily to acquire altimetry and images of the Earth at different wavelengths, each of which carries information about specific properties. Multispectral imagery is the task of measuring light in multiple electromagnetic spectral bands and is strongly employed in Earth observation tasks [1]. Such pictures are multidimensional representations of a portion of the Earth's surface and atmosphere, encoding light's direction of arrival, intensity, wavelength, and time of measurement. However, Earth observation poses a series of challenges that force us to take performance trade-offs.

The main property that comes to mind when designing a remote sensing system is resolution. Resolution is a general property that can be applied to different kinds of measurements. It is the minimum distance between the values measured from two objects that the system is able to distinguish [2]. Even though the resolving capability is higher when the resolution is low, it is usually spoken of as high resolution.

In satellite imagery, there are four types of resolution, sometimes with reciprocal conflicting specifications, which are: spatial, radiometric, spectral, and temporal resolution [3].

Geometric or spatial resolution is the area covered by a single pixel [3]. It refers to the ability of a detector to resolve objects that are spatially close. A good geometric resolution prevents a single pixel from acquiring mixed data from close areas with different properties, which could lead to noisy spectral features. The smallest is the area covered by a single pixel; the better the resolution.

The currently most advanced space missions achieve up to decimeters geometric resolution on the ground, with commercial platforms like WorldView outperforming governmental spacecraft. The space technology still cannot match the quality of airborne sensing systems, but it provides many logistical advantages over them.

Radiometric resolution is the amount of information reserved for an intensity value measured by a single pixel [3]. It can be interpreted as the capability of a digital system to resolve close light intensity values. Low-resolution radiometry can make it impossible to distinguish objects under the same light exposure. A commonly selected value for such a parameter is 8 bits, but more modern systems like QuickBird [4] and Sentinel [5] implement resolutions of 11 and 12 bits, respectively.

Spectral resolution is the ability of an instrument to discern finer wavelengths [3]. Each material has specific interactions that involve light emission and reflection in specific spectral channels. Being able to decompose the captured light into different fine-grained spectral bands is fundamental to distinguishing different kinds of matter and phenomena. We talk about multispectral with tens of bands and hyperspectral with enough resolution power to handle hundreds of bands.

In recent years, along with the effort put into improving the satellites' geometric resolution while miniaturizing them, a trend in increasing the spectral resolution has also emerged.

Temporal resolution is the time employed by a spacecraft to observe a given area again after the previous flyby [3]. It can be interpreted as the capability to resolve events that are temporally close. For a satellite system, this property is typically measured on a scale of days and is mostly dependent on the revisit time granted by the orbit of the spacecraft. Other important factors are the number of satellites put on the same orbit and the agility of the detectors, which may flexibly increase the resolution on demand by observing from directions other than the zenith.

Today, the previous constraints of weekly revisit times have been shifted toward daily-scale time resolutions by coupling two satellites in LEO orbit. However, a trend in launching numerous constellations is aiming at improving this scale even more.

In practice, all these different performance metrics share dependencies on the spacecraft's orbit and payload characteristics. However, most often, optimizing one implies giving up performance on the others. For instance, the choice of the orbit affects both the revisit time and the distance of the spacecraft from the surface. Although the first can be virtually reduced to zero, achieving a very high temporal resolution, the latter implies a loss in the spatial resolution. Another example of conflicting requirements is spectral and spatial resolution. Increasing the number of detectable bands means reducing the size of such bands, and conversely, the amount of photons received for each band and from each pixel. A lower measured light intensity worsens the overall spatial definition. For such a reason, the systems previously mentioned with high spatial resolution operate in the panchromatic band, where the total integral contribution over all the electro-optical bands is acquired.

While dealing with performance trade-offs over all the dimensions of a multispectral image, the same parameters tuned to optimize the resolution shall also be constrained to other important mission requirements. For example, a desired surface coverage or a specific narrow band of interest to be analyzed can limit the choice of the orbit and the on-board technology.

Provided some context about the performance metrics in remote sensing, it is worth delving into some concrete operational examples to better understand what today's trend is in actual space missions.

Among the most relevant optical observation space programs, Landsat [6] is a joint collaboration between NASA and USGS aimed at multispectral coverage of the Earth's surface. Across the Landsat missions, the choice of the remote sensing technologies remained coherent. This makes it possible to conduct longitudinal studies on data gathered over a long operational time of approximately 50 years. Over the decades, an increase in all the resolution types has been achieved, from the launch of Landsat 1 up to Landsat 9, which has 30 meters spatial resolution on the ground per pixel, 12 bits radiometry, a bi-weekly temporal resolution, and observes 11 spectral bands.

Another renowned program is ESA's Copernicus [7]. It involves a series of Earth observation missions called Sentinel [5], with the purpose of generating public data for environmental monitoring and security. As for Landsat, Sentinel spacecraft and payloads have been continuously developed and launched over the last decades. However, each Sentinel carries its specialized payload and takes advantage of two satellites to increase its time resolution. Together, they have collected a huge dataset from multispectral imaging, thermal radiometry, and radar altimetry, and continue to do so. Sentinel 2 detects over 12 bands, with a 5-days revisit time, 12-bit radiometry, and up to 10 meter spatial resolution.

Different from Sentinel and Landsat, which provide us with open-access products, WorldView [8] is an example of a commercial space program. Those are missions launched by DigitalGlobe that generate licensed optical and multispectral images with a very high spatial resolution in the panchromatic band, in the order of decimeters.

In the context of commercial space missions, Pleiades [9] missions by Airbus offer observation services with unmatched reactive tasking ability.

In conclusion, designing a space mission for Earth observation requires a proper definition of the requirements. Among these requirements, spatial, radiometric, spectral, and temporal resolution are critical and conflicting. The choice of the payload and the orbit shall be oriented to optimizing the performance while taking trade-offs functional to the mission objective. Across the years, governmental and commercial space missions have been monitoring the Earth for long periods, providing invaluable data while improving their observation capability up to today's state of the art.

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