Toward a Concept of Space-based Optical Seismometer

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Abstract
Imaging seismic waves and transient displacements at the Earth surface would be an invaluable source of information to investigate earthquake processes, various geomorphic processes and ice dynamics. A temporal sampling of the order of 1Hz would be required to measure seismic waves measurement, while hourly to daily sampling would be sufficient for a number of transients (postseismic deformation, slow events, transient ice flow). Ideally we would wish a centimetric to decimetric accuracy on the ground motion measurements with independent measurements at about every 100m. Here we discuss the characteristics of a potential geostationary space mission that would allow such measurements. We envision a monolithic telescope with a 5 m diameter primary mirror as well as larger but more complex synthetic aperture optics, coupled with an ultra-large-area CCD image sensor (about 1x1m in size) or a very-large CCD in association with an opto-mechanical field scan, and with enhanced data management and on-board processing. Our study demonstrates that most of the technology required for such a system already exists, that a monolithic mirror would be large enough both in term of geometry (pixel size) and radiometry, but that some major advances are required to meet the proposed performance .

Introduction
Measuring displacements at the Earth surface from space is of major interest to Earth Sciences in general. Three complementary techniques are commonly used. They are GPS, differential SAR interferometry, and sub-pixel correlation of optical images. The main limitations are that GPS lacks the dense spatial sampling needed to investigate certain processes, and both SAR and optical imagery suffer from a poor temporal sampling, which is, at best, a couple of days with existing systems. Unfortunately, seismic waves, post-seismic deformation, transient , glacier surge, and a number of other phenomena of interest typically occur at temporal scales ranging from one second to one day, can thus not be estimated using current imaging systems. An optical imaging system on a geostationary platform could therefore be a promising avenue. The deployment of such optical devices has thus far been limited to meteorological and other applications [2]. These systems have only a coarse spatial resolution. The 36,000 km altitude of geostationary satellites would require the use of complex and expensive Synthetic Aperture Optics devices for the kind of high ground resolution that we envision here.
Hereafter we first discuss the basic properties of the telescope, including its geometry and radiometry. A dedicated very-large-array CCD image sensor is discussed in a second part, and finally, in a third part, we address the data management and processing challenges.

Basics of a Dedicated Optical Device
Geometrical Constrain on Optical Aperture
Experience from heliosynchronous observing satellites and from image correlation techniques suggest that horizontal ground displacement can be measured with accuracy up to $1/100^{th}$ of the pixels [1]. The maximum diameter for a monolithic mirror that could be launched on a geostationary orbit is about 5 m, assuming the current limitation of the Ariane 5 launcher. At optical wavelength and from a geostationary orbit, such a telescope would provide a ground resolution of about 5 m. Therefore, under ideal conditions, it would be possible to resolve horizontal ground displacement with 5 cm accuracy (rms).

Two questions then arise to enhance this performance: a) Can we improve the angular resolution by using a larger telescope? and b) Can we further improve the accuracy of estimated ground displacements?

Monolithic Mirror vs Synthetic Aperture Optics

Co-phasing an array of optical mirrors is known to improve the angular resolution of telescopes, and various concepts of optical interferometers have already been developed, including Fizeau like interferometers (e.g., JWST, Keck) and Michelson interferometer [3]. The former configuration is already in use for astronomy but may present excessive system size, and the later configuration is still under development to improve the field of view. Although it has been demonstrated that a Synthetic Aperture Optics device could enhance the ground resolution by a factor about 3 [3], and thus the accuracy of offsets measured, the cost of such a system would be very high. In the following, we only consider the potential of a 5 m diameter monolithic primary mirror.

Image Sensor

Geometry

We consider a reference field of view of 1000x1000 km on the ground, which is a reasonable size for the real-time monitoring of a given seismogenic zone. A wider field could potentially be proposed using an opto-mechanical scanning procedure. Imaging the whole scene using a unique image sensor would then require an ultra large CCD array with a size of about 1x1 m (200,000 x 200,000 pixels, 5µm in size). Current state of the art very-large-area CCDs are formed by stitching building block of small CCD arrays [4], and such a large sensor would have to be developed based on a similar technology. The MTF of the optics would have to be adapted to be low at CCD Nyquist frequency to avoid aliasing effects on ground motion estimation.

Radiometry

State of the art CCD sensors with vertical anti-blooming (VAB) provide a pixel charge capacity of about 50ke-, and an associated read noise as low as about 10 electrons at 25Mhz pixel rate (horizontal clock frequency), yielding a dynamic range better than 70 dB [4]. Readout frequencies are even higher with line-scan technology (6k pixels lines red at 160 Mhz). To monitor transient seismic waves, the desired temporal bandwidth for image acquisition has an upper bound of about 1Hz. Although the effective CCD readout time will highly depend on the size of the CCD, readout frequency should not be a strong limitation on a instrument providing images at a rate better than 1Hz.

Integration time is of major interest in the perspective of monitoring transient seismic waves. If it is too short, the signal to noise ratio will be poor, if it is too high, the requested need for data every about 1s will not be addressed. Several parameters put tight constraints of the integration time: surface albedo, which can be realted to the sun elevation angle, the numerical aperture of the optical device (telescope diameter/ focal length), the sensitivity of image sensor, which also depends on the sensor's spectral bandwidth, and the noise equivalent power (NEP). As an example, the optical devices of SPOT 1-4 satellites (HRV, High Resolution Visible) include a telescope 0.33m in diameter and about 1/100s integration time; its results a signal to noise ratio of about 200 in the panchromatic band. Given an identical integration time, the same signal to noise ratio would require a geostationary telescope as large as 17 m in diameter. For a geostationary telescope of 5 m in diameter to perform radiometrically as well as SPOT sensors, an integration time of about 0.1s would then be necessary. This suggests that such system could yield an image rate of several images per second, which is far better than the upper temporal threshold for geophysical applications (1 Hz or less).

Data management and processing

Data management

Let us consider images of 200,000 x 200,000 pixels in size, 16 bits in dynamic range and 1 Hz in repeat time. The data volume would thus be about as large as 80 GB/s. It would be neither reasonable neither of interest to download all the data back to Earth. Most of the signal processing is thus to be considered on board, although some images could be transmitted to the ground at a lower frequency.

Data processing

Normalized cross correlation of sliding windows NxN in size (N=16, 32, 64 pixels typically) in the Fourier domain has become the standard procedure to derive ground displacement from a pair of images bracketing a geophysical event [1]. The present situation is very different and it is actually more ideal to measure deformation between images. Indeed, both temporal and geometric decorrelation of consecutive images will be negligible because temporal decorrelation induced surface changes, as well as variation in pointing incidence angle (e.g. topographic parallax effect) and sun angles will be negligible (about 4.10^{-3} degree per second).

In this context, to gain in spatial resolution of the measurement, standard image cross-correlation could be mixed with some other techniques inherited from video processing, including:
1. optical flow, because the radiometry would slowly vary with time,
2. Kalman filtering, in order to benefit from a large set of images.

In the case of synthetic aperture optics, the matching procedure may also account for the complexity of the Modulation Transfer Function (MTF) that may include zeros and thus may not allow for direct normalization of Fourier transforms of the sub-images.
Atmospheric turbulence is to be neglected because the atmospheric phase screen is located close to the ground and no particular development is foreseen to filter out the induced effects. Of course, such a device would only be operated in day light and clear sky conditions.

Discussion-Conclusion
To conclude, the performance required to measure seismic waves and various kind of transient surface displacements of geophysical origin could be achieved from an optical geostationary device using a monolithic primary mirror of 5 m in diameter (or, with much more complexity, a larger telescope from Synthetic Aperture Optics), and an ultra-large-CCD image sensor with dedicated processing. The technology required for most parts of the instrument concept is already available (see figure 1), the principal challenge therefore residing in the design and the development of the ultra-large CCD sensor though the option for a smaller CCD associated with an opto-mechanical field scan is still open. The stability of the platform has not been addressed because, state of the art technology show a stability of the line of sight that is about 10^{-7} rad at considered temporal frequencies [2]. From a geostationary orbit, a variation of the pointing device would simply induce global translation of the motion being measured by about the size of one pixel, which could easily be compensated during processing.

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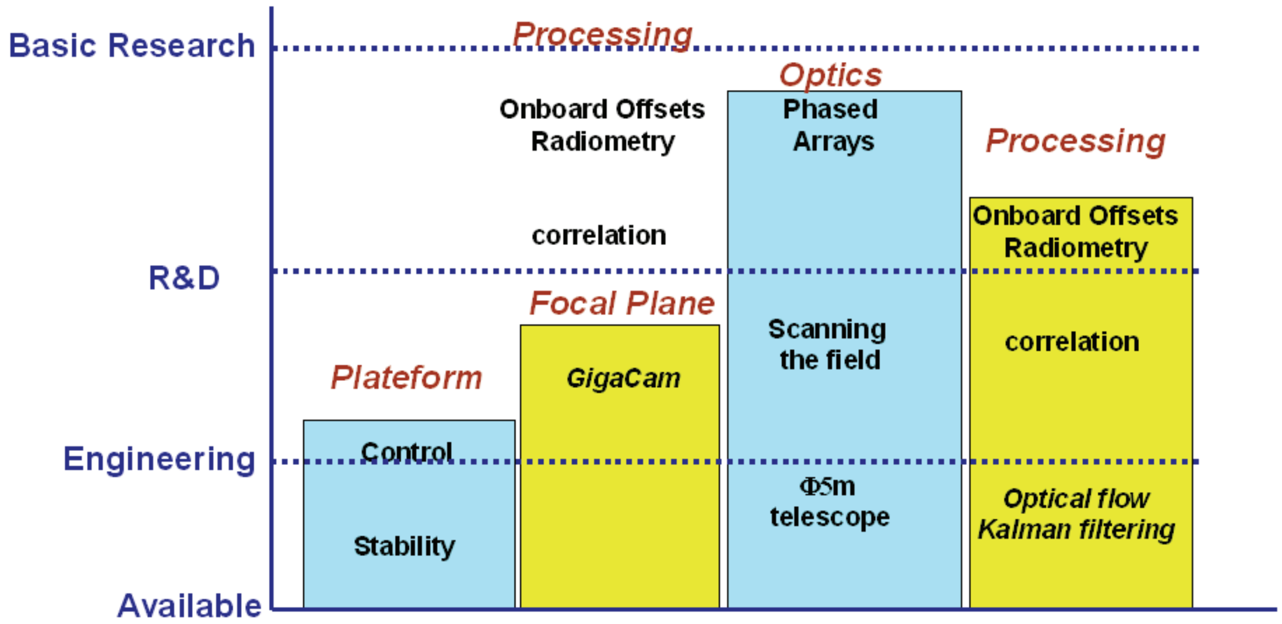

Figure 1 technology readiness levels-like of basics technology required for geostationary imagery of geophysical ground deformation.