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Review

# Motion detection using near-simultaneous satellite acquisitions

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ABSTRACT

A number of acquisition constellations for airborne or spaceborne optical images involve small time-lags and produce near-simultaneous images, a type of data which has thus far been little exploited to detect or quantify target motion at the Earth's surface. These time-lag constellations were for the most part not even meant to exhibit motion tracking capabilities, or these capabilities were considered a drawback. In this contribution, we give the first systematic overview of the methods and issues involved in exploiting near-simultaneous airborne and satellite acquisitions. We first cover the category of the near-simultaneous acquisitions produced by individual stereo sensors, typically designed for topographic mapping, with a time-lag on the order of a minute. Over this time period, we demonstrate that the movement of river ice debris, sea ice floes or suspended sediments can be tracked, and we estimate the corresponding water surface velocity fields. Similarly, we assess cloud motion vector fields and vehicle trajectories. A second category of near-simultaneous acquisitions, with much smaller time-lags of at most a few seconds, is associated with along-track offsets of detector lines in the focal plane of pushbroom systems. These constellations are demonstrated here to be suitable to detect motion of fast vehicles, such as cars and airplanes, or, for instance, ocean waves. Acquisition delays are, third, also produced by other constellations such as 'trains' of satellites following each other and leading to time-lags of minutes to tens of minutes, which are in this contribution used to track icebergs and features of floating ice crystals on the sea, and an algae bloom. For all acquisition categories, the higher the spatial resolution of the data and the longer the time-lag, the smaller the minimum speed that can be detected.

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## 1. Introduction

Lateral motions on the Earth's surface happen at a large range of magnitudes and rates. The ability to quantify them from ground, air or space using repeat imagery depends, in principle, on the precision of the method used, the total displacement between two data acquisitions, the rate of displacement, and the existence of corresponding features in phase data (for radar) or amplitude data (for radar and optical sensors) that can be tracked over time. For instance, tectonic displacements, glacier flow, rockglacier creep, slow landslides or soil motion are typically measured using radar interferometry (e.g., Rott, 2009), or optical or radar offset tracking methods (e.g., Kääb, 2002; Kääb, Girod, & Berthling, 2014; Leprince, Barbot, Ayoub, & Avouac, 2007b; Strozzi, Luckman, Murray, Wegmuller, & Werner, 2002). Depending on the displacement rates and the visual or phase coherence over time, the temporal baselines applied may vary significantly, typically from days to years. In the following, we refer to temporal baselines as time-lags.

Much research and applications are available for time-lags of weeks to years and decades from air and space, or for ground or laboratory applications with a range of typically shorter time-lags (e.g., particle image velocimetry, PIV). Short airborne or spaceborne time-lags on the order of milliseconds to minutes, up to a few hours, and their application to Earth surface processes are, however, very little and not systematically exploited. Such near-simultaneous data have, however, the potential to depict motion and processes that could so far hardly be quantified over larger areas. Along-track radar interferometry has, for instance, been demonstrated for ocean currents, river flow and vehicle movement (Baumgartner & Krieger, 2011; Goldstein & Zebker, 1987; Romeiser, Suchandt, Runge, Steinbrecher, & Grunler, 2010; Romeiser et al., 2007; Siegmund, Bao, Lehner, & Mayerle, 2004). Also, synthetic aperture radar (SAR) focussing, which is based on the Doppler effect, may image moving objects in a displaced position within the image depending on the additional Doppler effect their motion introduces.

The present overview focuses on optical data with airborne and spaceborne time-lags on the order of milliseconds to minutes. A few related studies are currently available with specific applications to river ice debris (Beltaos & Kääb, 2014; Kääb & Prowse, 2011; Kääb, Lamare, & Abrams, 2013), ships (Takasaki, Sugimura, & Tanaka, 1993), cars (Reinartz, Lachaise, Schmeer, Krauss, & Runge, 2006), sun glitter (Matthews & Awaji, 2010), and waves (De Michele, Leprince, Thiebot, Raucoules, & Binet, 2012). These studies are referred to in more detail later in this contribution, but provide no general view on the exploitation of near-simultaneous images for Earth-surface motion detection. The present article gives the first systematic overview on short acquisition time-lags in Earth observation datasets, and demonstrates a number of novel applications. Typically, these time-lags stem from constellations that are for the most part not meant for motion tracking or where time-lags are even considered a drawback. First, we will elaborate on the acquisition constellations that cause time-lags. After describing methods that can be used to explore and quantify motion in near-simultaneous data, we demonstrate and discuss a selection of applications using case studies.

## 2. Near-simultaneous acquisition constellations

Short optical time-lags arise from two acquisition principles:

A first principle of time-lags, which is however not the main focus of this contribution, stems from repeat acquisitions from, at least approximately, stationary sensors (with respect to the Earth surface), such as on balloons, zeppelins, helicopters, satellites with video devices, or satellites in geostationary orbits. Exploitation of time-lag data from geostationary platforms is well established from weather satellites to monitor cloud motion, but also instruments for higher resolution and thus with smaller movements becoming detectable are under consideration (Michel et al., 2013). Time-lag data can also be achieved through revisit of an acquisition position by the same or another platform within short time (e.g., different satellites following each other on similar orbit, 'trains'; repeat airphoto flight lines).

A second principle, and the main focus of this contribution, consists in along-track angular differences between the acquisition directions of two or more images (Fig. 1). The effective time-lag is then primarily a function of the difference in looking angles to the target, the average speed of the sensor between acquisitions and its height above target. Further influences on the time-lag stem from the deviation of the sensor flight path from a straight line or arc, and from the geometry of the angular constellation (Fig. 2).

The time-lag can be estimated from the looking angles as follows. For a geocentric circular orbit around Earth (Fig. 1)

$$b = b_1 + b_2 = (\beta_1 + \beta_2)(R + H) \tag{1}$$

where $b$ is the length of an arc between two oblique acquisition looks, $\beta_1$ and $\beta_2$ the corresponding angles (in radians) at Earth centre against target nadir, $R$ the Earth radius and $H$ the sensor height above Earth surface.

The time difference between the views is for an average sensor speed $|\vec{v}|$

$$\Delta t = t_2 - t_1 = \frac{b}{|\vec{v}|}. \tag{2}$$

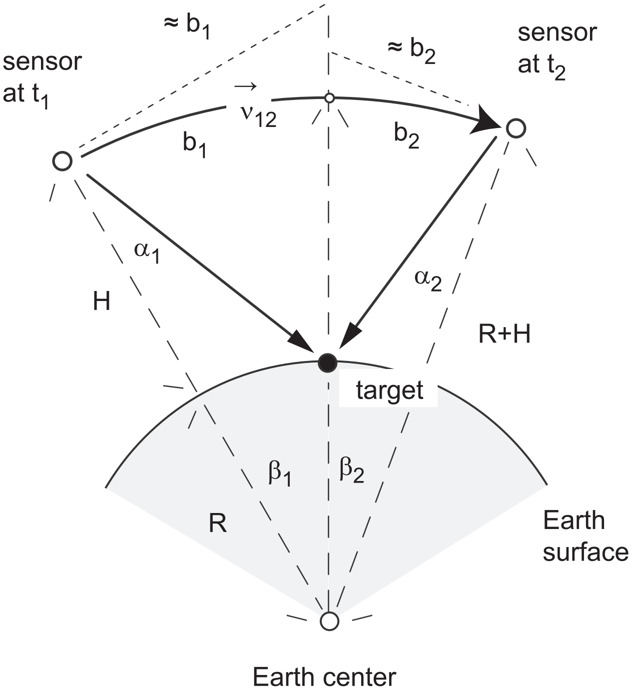

**Fig. 1.** Scheme of a single-pass near-simultaneous acquisition causing a time-lag $t_2$-$t_1$. Earth radius $R$, flying height above Earth surface $H$, angles $\alpha$ and $\beta$, and arc $b$.