

Slide 1 – Title Slide

Hello and welcome to Week 12, part 3 of EGM310: Observing surface motion. In this lesson, we will learn about how we can use satellite images to observe and measure the motion of different features on the Earth's surface.

Slide 2 – Surface motion

We are able to see relatively slow, large movements of surfaces from space. Because of the slight offset between different bands, we can sometimes seem faster movements, such as cars on a motorway or airplanes in the air, but I'm talking here about things such as glaciers, as we can see here, or permafrost. We can also track landslides from space – not normally rapid landslides such as debris avalanches (although we might sometimes get lucky and be able to partly observe them due to band offsets), but slower, long-term creep of slopes is something we can often monitor from space. We can also see ground subsidence due to changes in aquifers – how the ground actually lowers or raises in elevation due to changes in water levels underground. We can also observe volcanoes – how changes in magma storage within the volcano can cause the ground to move up or down. Finally, we can also observe earthquakes – not usually while they happen, but we can use satellites to track displacements and see where and how an earthquake has had an effect. We can also use both optical and microwave sensors to observe motion, using different techniques.

Slide 3 – Offset tracking

The first technique we'll talk about is what's known as 'offset tracking', which is normally done using optical images. To do offset tracking, we first need at least two images, spaced far enough apart in time to be able to see displacements, or motion. These images also need to be orthorectified, otherwise the differences we observe might be due to uncorrected geometric errors, rather than actual movement on the ground. They should also be registered to each other, though there are ways to do this as part of the process of offset tracking. The basic method is as follows. First, we start with a small sub-region, also known as a template, or chip, of the first image. Starting from the same location in the second image, we search for our reference template by moving it around the second image and comparing what we find, a process known as template matching. Normally, we're looking for some sort of correlation between the two image chips – the higher the correlation, the more likely it is that we've found a match. The example here shows the reference chip with a size of 100x100 pixels, and the search chip, with a size of 150x150 pixels; it also shows the correlation peak at the location where the reference chip appears to have moved. We can estimate the correlation in a number of ways; perhaps the most common is what's known as normalized cross-correlation, which helps eliminate variations in illumination that might cause false matches. Another type of technique is what's known as Phase, or Orientation, correlation – this uses the image frequency, rather than the image itself, to do the matching. By doing this in a semi-regular grid in the image, we can estimate the displacement field of the image; this example, taken from the ImGRAFT software, shows the velocity of Helheim Glacier in Greenland.

Slide 4 – Example: Vavilov ice cap

This slide shows an example of the results for Vavilov ice cap, an ice cap in Severnaya Zemlya in the Russian Arctic. Around 2013 or so, a portion of this ice cap began to collapse, flowing out into the ocean in rather spectacular fashion. The first image, from March 2015, shows the glacier velocity at a point relatively early in the collapse – we can see the ice spreading out from the main body of the ice cap, with the highest speeds, represented by red, above 10 meters per day. One year later, in March 2016, the ice lobe has expanded dramatically, with high speeds reaching well into the interior of the ice cap. We'll come back to some more examples of glacier flow later in the lesson.

Slide 5 – Example: river flow

Recall that ASTER has both a nadir and a backward-looking camera. These two cameras observe the same portion of the Earth's surface, with about 60 seconds of separation. We can use this to track faster motion, such as river flow, provided that we have objects to track. This example, from a set of 9 different ASTER images that flew almost perfectly along the Lena River in Siberia, shows the variation in flow along nearly 600 km of river, in May 2011; a close-up here shows some of the detail that can be observed. These examples came from a 2013 study demonstrating the potential of ASTER images for observing changes in river flow; since then, similar applications to observe circulation patterns in ice-covered fjords have also been demonstrated.

Slide 6 – Interferometric SAR (InSAR)

Moving away from optical imagery, we can also use synthetic aperture radar, or SAR, to observe ground motion. Remember that the phase of a signal refers to its partial wavelength. In this example here, we have a satellite sending a signal toward a target; with the given wavelength, we have one, two, three full wavelengths of distance, plus a small bit leftover – this is the phase. For a radar signal, the phase has two different components. The first is a deterministic component, which comes from the distance between the sensor and the ground. The second component is random, caused by scattering from 'small' objects – meaning objects that are smaller than the spatial resolution of the sensor. Similar to mixed pixels in optical images, these objects add up and contribute noise to the phase recorded by the sensor. Fortunately, because this is mostly random noise, we can use two images acquired at different times or from different locations to remove the random component and recover the deterministic component, which gives us our distance between the sensor and the ground; if we know the satellite's position, this gives us topography. As you can see from this image, this interferogram – so called because it's the pattern made by interference between the two radar signals – is ambiguous: it only tells us the topographic component within the full wavelength range. In order to measure topography, we have to do something called 'unwrapping' the interferogram, where we start with a point, or points, whose elevation we know, and move up or down along these fringes to calculate the true elevation. If we have three images that meet certain criteria, or two images plus a DEM, we can calculate the deformation, or motion, of the surface between the first and the last observation – this is a technique known as differential InSAR, or dInSAR. This gives us the deformation in the line of sight of the sensor only – in order to get multiple directions, we need multiple look angles. This process works

great for small deformations – for larger deformation, it can be hard to accurately compare the two signals and recover the deformation signal.

Slide 7 – Example: subsidence due to groundwater pumping

One common application of differential InSAR is monitoring changes in ground elevation due to changes in terrestrial water storage. For example, this study from 2001 shows the seasonal elevation changes in Los Angeles as a result of groundwater pumping and replenishment. The changes here are tiny – less than a decimeter – but dInSAR is particularly sensitive to these small changes, again depending on the wavelength of the sensor, and how often we can get repeat images to observe changes.

Slide 8 – Example: volcano studies

We can also apply differential InSAR to study volcanoes. This example is from Ugashik-Peulik, a volcano in the Aleutian Islands in Alaska. The last recorded eruption of this volcano was in 1814, and it has been generally quiet since then. Using differential InSAR, we can see the deformation pattern of the volcano as estimated by images from 1995 and 1997 – we can see a nice, clear bull's-eye pattern of deformation. This pattern is caused by the inflation of a magma reservoir by about 0.04 cubic km at a depth of about 6 km, resulting in an observed ground uplift up to about 17 cm in the center of the pattern. Remember that underneath a volcano, we have a magma chamber that stores molten rock, or magma, that occasionally comes to the surface in the form of an eruption. Changes in the amount of magma can cause the ground above the magma chamber to move up or down – and just like with groundwater changes, we can measure this from space. We can then use mathematical models to estimate the change that lead to the observed deformation, helping us to monitor volcanoes and learn more about how they work. For this particular volcano, no eruption occurred at that time – not all movements of magma result in eruptions – but it's nice to know that we can keep track of these things.

Slide 9 – SAR offset tracking

Similar to with optical imagery, we can also do offset tracking with SAR. Radar images have speckle – they don't look perfectly clear; this is partly due to the influence of the same “small” scatterers that contribute the random phase component. If we look at an optical image of snow on top of a glacier, it's fairly uniform – there's some differences due to topography, but other than that we don't see much variation. In a SAR image, though, we see a significant amount of noise, or ‘speckle’. We can use this speckle for offset tracking – as long as it's coherent from one image to the next, it gives us a way to track offsets from one image to the next. Unlike InSAR, this gives us a displacement in the image coordinates, rather than the line of sight – thus, we can recover a velocity field of 2-dimensional motion using this technique. This works better for larger deformations, though – in the interior of the ice sheets, where velocities are on the order of less than 10 meters per year, we normally have to stick to InSAR techniques to measure motion.

Slide 10 – Example: glacier acceleration

This technique provides an invaluable tool for monitoring the peculiar behavior of glaciers. A glacier surge is a periodic acceleration of about 10 to 100 times the ‘normal’ background speed. These phenomena occur on glaciers all over the world, including in the high Arctic. The example here shows the development of a surge of Tunabreen, a glacier on Svalbard. In December 2016, Tunabreen began a surge – we can see the increase in speed begin near the terminus of the glacier here, and move up the glacier over time. Another example from Svalbard, this figure shows the development of a surge on Negribreen, which began surging in early 2016. During the polar night, we can’t use optical images due to the lack of sunlight. This is also true in times of heavy cloud cover. SAR satellites, and offset tracking, provide a way to continue to study and observe glacier surges, even when we can’t see them with optical sensors.

Slide 11 – Summary

In this lesson, we have discussed a number of tools and techniques available to study motion or deformation on the Earth’s surface, using both optical and microwave sensors. Which technique we use depends on our particular application, and the availability of data. Optical data have seasonal and weather-related limitations that might make some applications difficult or impossible; InSAR is a powerful tool, but it can be heavily affected by changes in surface moisture or composition, and it can’t be used to study larger deformation. Speckle tracking is great for larger deformation, but it, too, is sensitive to surface moisture and composition.

Slide 12 – Additional resources

I’ve included links to a number of videos here, including two on measuring ice motion from satellites and other imagery, as well as a longer explainer on InSAR and how we can apply satellite observations to study volcanoes. I’ve also included a link to an article about the surge of Tunabreen, if you’re interested in seeing a bit more information on glacier surges. That’s all for this lesson – I hope you found it interesting, and if you have any questions, please don’t hesitate to e-mail me or post in the discussion forum on blackboard. Bye!