Deformation pattern of the 17 August 1999, Turkey earthquake observed by satellite radar interferometry

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On 17 August 1999, 3 AM local time, the area around Izmit, Turkey suffered a strong earthquake: 7.5 on the Richter scale (KNMI). The earthquake was caused by an accumulation of stress during many years around the North Anatolian fault zone, where the Anatolian plate and the Eurasian plate meet.

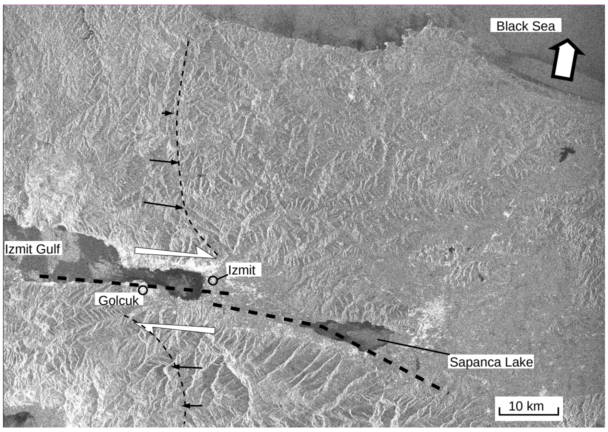

Figure 1: Radar intensity image. This image is shown for orientation, and shows the Black Sea in the north-east, Izmit Gulf in the west, and Sapanca lake in the center. Topography is visible in the south. Urban areas such as Izmit can be recognized by the bright intensity.The North Anatolian fault is indicated by the fat dashed line.

Figure 1 is the radar intensity image of the European ERS-2 satellite, acquired from 789 km height. Variation in the brightness of the image occurs when rough areas reflect more energy back to the radar than smooth areas. It is clear to see how urban areas around Izmit reflect much energy back to the satellite, just as the the side of the mountains faced to the satellite. Water areas such as the Izmit Gulf are smoother in the eyes of the radar, and reflect less energy back to the satellite, which gives them a dark appearance. The dotted horizontal line indicates the location of the North-Anatolian fault.

Figure 2 is the so-called 'interferogram', obtained by comparing two radar images (of 13 August and 17 September). Using a color code it is shown how the range between points in the terrain and the satellite have changed in between the two acquisitions. If the earth would have remained unchanged inbetween the two acquisitions, all land areas should have the same color. Between these two acquisitions, however, the earth has deformed considerably as a result of the 17 August earthquake. The pattern of the color cycles is used by geodesists and geophysicists to accurately measure which deformations occured. Just as the year rings of a tree can be counted to reveal its age, it is possible to calculate the amount of deformation between two points in the interferogram by counting the color cycles.

Interpretation of the interferogram

How should the color changes in the interferogram be interpreted? As a rule of thumb one could say that two points which are on the same color line suffered the same amount of deformation. Of course it is very important to make sure that the route between the two points does not cross any other colors! As long as this is possible, it is possible to verify whether the two points suffered the same amount of deformation.

The synthetitic aperture radar (SAR) of ERS-2 measures the phase, a number between 0 and 360 degrees, of the reflected pulse. Every cycle of 360 degrees corresponds with the semi-wavelength of the radar. For the 5.6 cm wavelength of ERS-2 this implies that every full color cycle in figure 1b corresponds with 2.8 cm of deformation, directed to the radar or away from it. In this case the color cycles mean

- yellow-blue-red (YBR): deformation away from the radar, and
- yellow-red-blue (YRB): deformation towards the radar.

As it is not possible to determine absolute deformation rates, we can only measure the relative change in range between two points in the interferogram. A

Example

If we count the number of color cycles, or 'fringes', from the Black Sea coast to the northern shores of Izmit Gulf, we find 27 cycles. This leads to a change in

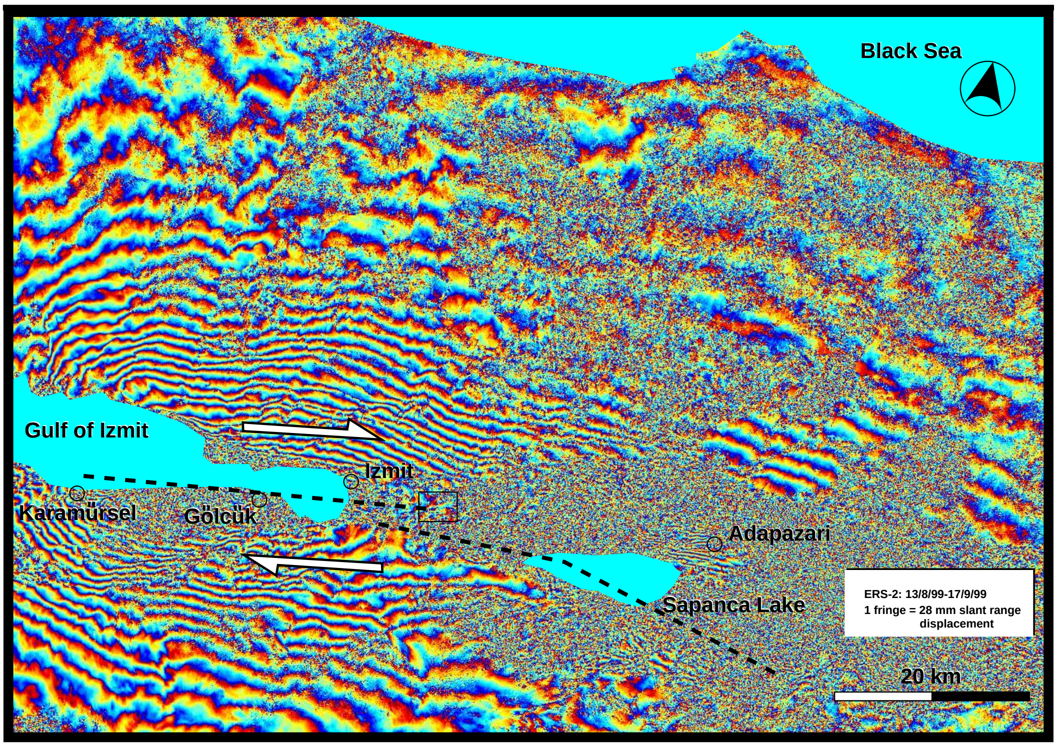

Figure 2: Radar interferogram, showing the difference in the distance between points in the image to the satellite between two radar acquisitions: 13 Aug 1999 and 17 Sep 1999. The change in range is expressed by the color cycles, where every cycle corresponds with 2.8 cm in the satellite line of sight.

range of 27 times 2.8 cm, or 75 cm. Counted along this path (North-South), the order of the colors is YBR, which leads to the conclusion that the northern shores of Izmit Gulf has moved 75 cm away from the radar, with respect to a point at the Black Sea coast.

Here, the measured 75 cm is the change in range in the line of sight to the radar. Since it is known that the deformation for this fault system is dominantly horizontal, we use the projection of the vector from the satellite direction to the surface, as shown in figure 3. This results in a multiplication factor of 2.6. This leads to the conclusion that the northern shore of Izmit Gulf has moved 1.95 m away from the satellite, with respect to a point at the Black Sea coast.

From the interferogram it can be concluded that it is very difficult to count the color cycles near the fault. This is caused by two mechanisms:

- Near to the fault the color cycles are too close together, in fact, they are so close that they are on top of each other. This makes it impossible to count them unambiguously.

- In order to construct a good interferogram, the structure of the earth's surface should remain unchanged as much as possible in between the two radar acquisitions. It is allowed that the area

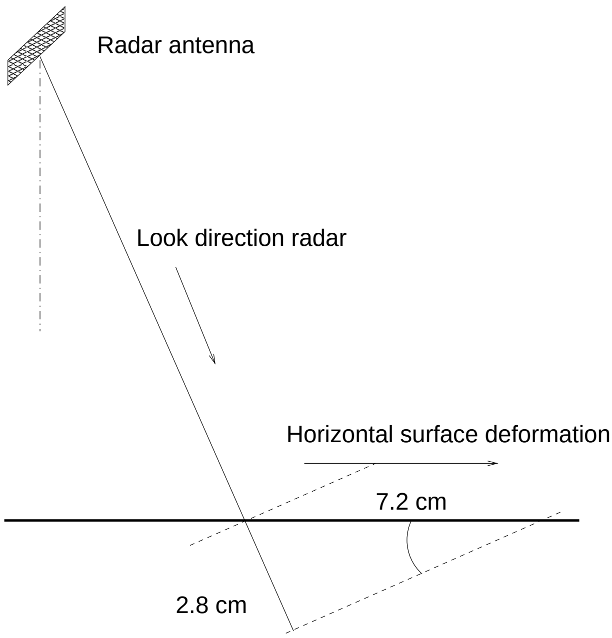

Figure 3: The look direction of the radar, approximately 23 degrees, results in the conversion of the deformation in the line of sight (2.8 cm per color cycle) to 7.2 cm horizontally.

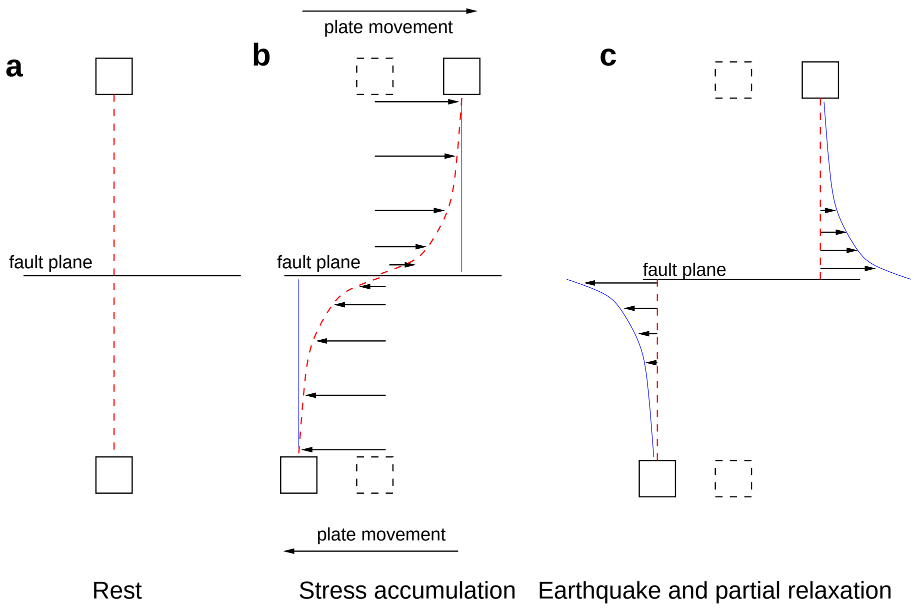

Figure 4: Schets van de deformatie ten gevolge van de plaatbeweging. In figuur a zijn de platen in rust, en kunnen we een rechte lijn trekken tussen de beide vierkantjes. Na verloop van tijd zijn beide platen ten opzichte van elkaar verschoven (figuur b): de vierkantjes zijn naar hun nieuwe positie verplaatst. Aangezien het breukvlak voldoende wrijving heeft, zullen de platen niet ten opzichte van elkaar verschuiven, maar elastisch deformeren. Er vindt dus spanningsopbouw plaats op het breukvlak. Ten tijde van de aardbeving is de spanning tussen de platen zo opgelopen dat ze op het breukvlak langs elkaar schieten. In figuur c, na de aardbeving, is dat aangegeven. De rode lijn, die in situatie b nog sterk verwrongen was, is nu min of meer terug in z'n oude positie. De blauwe lijn, echter, die in situatie b nog recht was, is nu dus sterk gekromd. In het interferogram zien we het gedrag van de blauwe lijn. Daar waar de blauwe lijn het meest gekromd is verwachten we dat de kleurencycli het dichtst op elkaar liggen.

moves as a whole, as long as the internal structure remains unchanged. It is clear that the devastated area around Izmit is very much disturbed by the earthquakes. This accounts for the noisy appearance of the interferogram at the location of the fault and the urban areas close to the fault.

Due to these two mechanisms we 'miss' the last part of the deformation when we count the color cycles, especially at the area where the deformation is most severe. Our result of 1.95 m from the Black Sea to Izmit Gulf will therefore be an underestimation. From field measurements it is known that deformation between 2 and 3 m have occurred near the fault, see figure 5. Near Izmit Gulf even deformations of 4-4.5 m have been observed.

Analysis of the observed pattern

In figure 4 it is shown how the observed pattern of color cycles can be interpreted. The fault plane represents the boundary between the Eurasian plate in the north and the Anatolian plate at the south side. The red line indicates the shortest distance between the two squares. The general plate movement causes the two squares to move away from each other, parallel to the fault plane (figure 4b). Because there is no direct slip along the fault, the red line is bent severely. The blue line indicates, at that time, the shortest distance to twe fault plane. Just after the earthquake, when both plates have slipped, the situation is as in figure 4c. As the accumulated strain has been partially released, the red line has moved to its new position. The blue line now indicates the amount of deformation between shortly before the earthquake and shortly after. In fact, the observed deformation pattern can be regarded as a mirrored version of the strain pattern before the earthquake; cf. the red line in figure 4b with the blue line in figure 4c.

Strain relaxation?

As long as the color cycles in the interferogram are parallel, both sides of the fault have moved parallel to each other. At those areas the strain which was accumulated over the years, is relieved at least partially. In the interferogram it can be observed that the color patterns are not parallel the entire range of the fault: in the western part they bend towards Izmit Gulf, both on the northern and the southern side of it. Assuming that this behavior continues through the crust under Izmit Gulf, this implies that both sides of the fault have not moved with respect to each other. In other words; at that location the plates have not moved, and a large part of the strain is still apparent! This could indicate an increased risk for future earthquakes, which is in agreement with general understanding of stress induced triggering. Proper ways to localize areas where strain accumulation is still in progress are essential in hazard monitoring and risk assessment.

Figure 5: 230 cm horizontal deformation near railway station Tepetarla in the region between Sapanca Lake and Izmit Gulf (Source: Esen Arpat, Kandilli observatory).