Developments in synthetic aperture radar interferometry for monitoring geohazards

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Abstract: In 1993 synthetic aperture radar (SAR) interferometry (InSAR) was introduced to the wider remote sensing community with the publication of the interferogram depicting the ground deformation caused by the Landers earthquake. Although the power of interferometry was demonstrated, the conventional technique has not always been applicable in all operational scenarios. Over the last few years, however, a number of technical developments have emerged that provide a higher precision of motion rates, the extraction of specific motion histories, and precise targeting. This paper examines uses of differential SAR interferometry (DifSAR) for monitoring geohazards. Limitations of DifSAR will be discussed: lack of coherence, atmospheric refraction and targeting. It will be shown how some of these limitations can be overcome with persistent scatterer interferometry (PSI), which detects slow ground motion with annual rates of as little as a few millimetres, reconstructing a motion history based on the European Space Agency's SAR image archive. The technique permits the estimation and removal of the atmospheric phase, achieving higher accuracies than DifSAR. PSI relies on the availability of pre-existing ground features that strongly and persistently reflect back the signal from the satellite. However, in highly vegetated regions, PSI may not be applicable because of the lack of natural scatterers. To ensure motion measurement of the ground or structures at targeted locations, the NPA Group is developing InSAR using artificial radar reflectors, such as Corner Reflectors (CRs) or Compact Active Transponders (CATs). Both reflector types are still undergoing validation tests, but results show a high phase stability in both cases.

Geohazards such as landslides, rockslides, earthquakes and sinkholes can pose a significant danger to humans and built infrastructure. Areas of extensive subsidence, such as that associated with underground coal mining, or the extraction of petroleum, brine or groundwater, can also cause costly damage to buildings and infrastructure. Large-scale measurement of ground deformation in endangered areas is therefore in the interest of the safety of the public and built environment.

Precision ground surveys can be carried out over sites to measure the stability of the terrain; however, such surveys are inherently expensive and in some cases can be dangerous to human life. Furthermore, some unstable areas can remain undetected by geoscientists, as a result of unfavourable survey conditions (e.g. thick vegetation, unsuitable weather conditions, absence of clear line of sight) or because ground movements are so slow that they are difficult to detect on the ground.

Monitoring ground movement with radar satellites has evolved in the last decade from conventional imaging InSAR to improved techniques such as persistent scatterer interferometry (PSI). The following two sections will give a short introduction to InSAR and illustrate applications for monitoring geohazards.

InSAR principles

Satellite synthetic aperture radar (SAR) systems transmit electromagnetic radiation signals at microwave and radio frequencies and measure the intensity backscatter and the time delay (phase) of the signals that are reflected back from objects in the signal path. The resulting SAR image has a spatial resolution of 10–20 m. Its brightness (i.e. the intensity of the measured backscatter) depends on the surface roughness, dielectric constant, moisture content and the slope of the local topography. The advantage of radar is that it is generally unaffected by atmospheric conditions, such as rain, dust and cloud cover, and can be used day or night. For more information the reader is referred to Hanssen (2001).

SAR interferometry (InSAR) is a technique in which the phase component of the returning radar signals of two or more radar scenes of the same location (see Fig. 1) are compared to allow the detection of ground movements to sub-centimetric precision (Gabriel *et al.* 1989). Although satellites' orbits are precisely controlled to allow for repeat-track missions, there will be slight differences in the position of the satellites when two images of the same ground location are taken from two different satellite passes in the same nominal orbital

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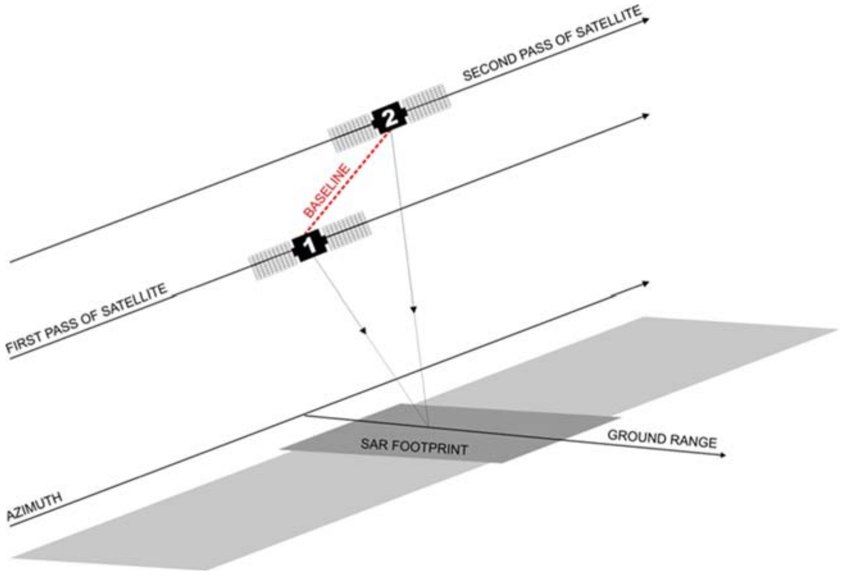

Fig. 1. Geometry of a satellite interferometric SAR system. The orbit separation is called the 'interferometer baseline' and its projection perpendicular to the satellite radar viewing direction is one of the key parameters to allow SAR interferometry analysis. The baseline is much smaller than the satellites' altitude, typically by about three orders of magnitude.

position. These differences allow for angular measurement similar to the principle used in optical photogrammetry, here with the angles not being measured directly, but inferred from distance measurements using trigonometry (Hanssen 2001, p. 17). For InSAR, the phase rather than the amplitude information is used from the returning signal to measure any change in ground height.

Data sources and issues

Currently three C-band SAR satellites are in operation: ERS-2, Radarsat-1 and Envisat. Table 1 presents some characteristics of these satellites and planned missions. ERS-2 and its precursor ERS-1 have built up a regularly updated archive of more than 1.5 million images worldwide. Envisat ensures continuity of SAR image acquisitions worldwide, and builds up a regular archive over some important and critical regions of the world. The Canadian Radarsat-1 instrument works on image request only.

InSAR measurements are generally limited by the characteristics of the sensor used to acquire the data. For example, measurements are possible only in the line-of-sight (LOS; i.e. viewing direction) of the sensor and scene updates depend on the repeat cycle frequency of the satellite. For long-term historical measurements over a given area, the data archive of the sensor needs to be checked for availability of sufficient and appropriate SAR data.

Also shown in Table 1 are details of the planned Radarsat-2 and TerraSar-X commercial missions. In addition, a C-band SAR satellite mission (Sentinel 1) is currently under discussion for the

Table 1. *Current and planned SAR imaging satellites*

Platform	Sensor	Country	Launch	Wavelength	Repeat pass (days)	Sensor incidence angle (deg)	Resolution (m)
ERS-2	AMI	Europe	1995	C-band	35	23	20
Radarsat-1	SAR	Canada	1995	C-band	24	20–50	≤8
Envisat	ASAR	Europe	2002	C-band	35	15–45	20
ALOS	PALSAR	Japan	2006	L-band	46	10–51	≤10
Radarsat-2	SAR	Canada	2006	C-band	24	20–50	3
TerraSar-X	SAR	Europe	2006	X-band	11	20–55	≤1

Table 2. *Three interferometric techniques used for ground motion measurements: DifSAR (differential SAR interferometry), PSI (persistent scatterer interferometry) and CR (Corner Reflector) or CAT (Compact Active Transponder) interferometry*

Method	Measurement periods	Need for archive data	Extents	Precision	Cost
DifSAR	Historical/present	Low	Map	Sub-centimetric	Low
PSI	Historical/present	High	Map of points	Millimetric	High
CRInSAR	Present	None	Specific locations	Sub-centimetric	Low to medium

European Space Agency's (ESA's) Global Monitoring for Environment and Security (GMES) Earth Observation (EO) component to provide continuity of InSAR applications beyond the lifespan of Envisat.

One of the GMES applications is the Terrafirma project (www.terrafirma.eu.com): this aims to establish a pan-European ground motion information service to detect millimetric ground displacements using PSI. Initially the service focuses on urban subsidence but it will eventually include earthquake zones, landslides, coastlines and flood plains. Terrafirma is one of a number of Service Element projects being run under ESA's GMES initiative, distributed throughout Europe via the national geological surveys.

InSAR techniques

Three methods for ground motion measurements by InSAR have evolved over the years. They are employed according to particular operational applications and are summarized in Table 2.

Differential InSAR (DifSAR)

DifSAR maps wide-area relative ground deformation and can cover an area of 100 km by 100 km in a single process. The output is a map of ground deformation showing sub-centimetric displacements in the LOS of the satellite. A key requirement is that the response characteristics of the ground cover in the area of interest have not changed significantly

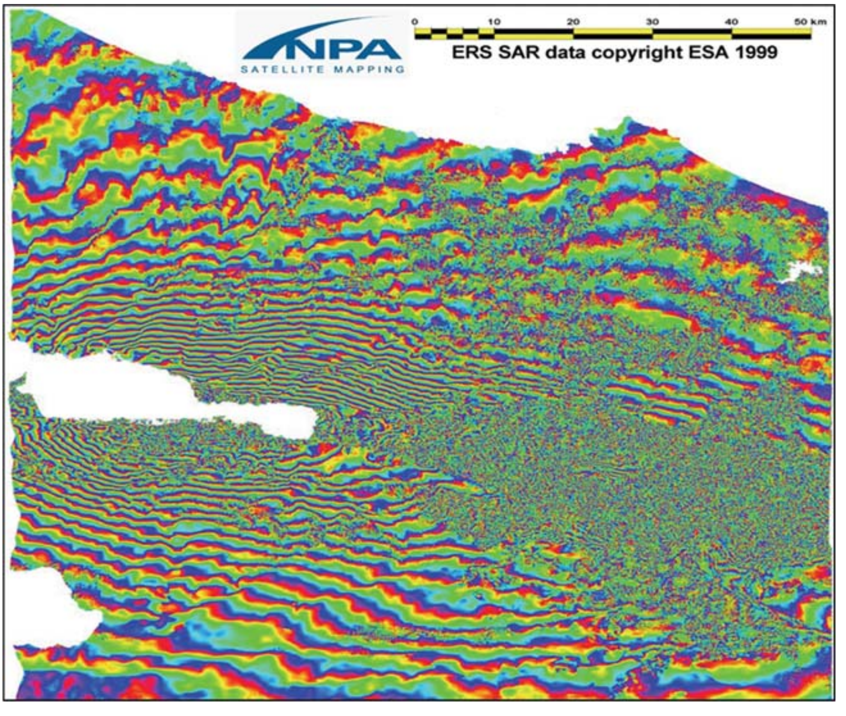

Fig. 2. Displacement map for the Izmit earthquake on 17 August 1999. The colour-coded contour cycles correspond to displacement of 2.8 cm in the line-of-sight of the satellite. Actual relative ground movement across the fault was 4 m horizontally. Image copyright NPA Group 1999; SAR data copyright ESA 1999.

between two image acquisitions. Depending on the ground cover, measurement periods from 24 days (rural environment) to 5 years or more (urban or arid areas) can be analysed. Key DifSAR studies include those by Gens & Van Genderen (1996), Bamler & Hartl (1998), Madsen & Zebker (1998), Massonnet & Feigl (1998) and Bürgmann *et al.* (2000). DifSAR has been applied successfully to map ground displacements resulting from:

(1) earthquakes: measurement of the build-up of elastic strain between earthquakes, as well as the actual deformation caused by an earthquake (Massonnet *et al.* 1993; Zebker *et al.* 1994; Peltzer & Rosen 1995; Wright 2002);

(2) volcanic deformation: inflation and deflation of volcanoes before and during eruptions, respectively (Amelung *et al.* 1999; Massonnet & Sigmundsson 2000);

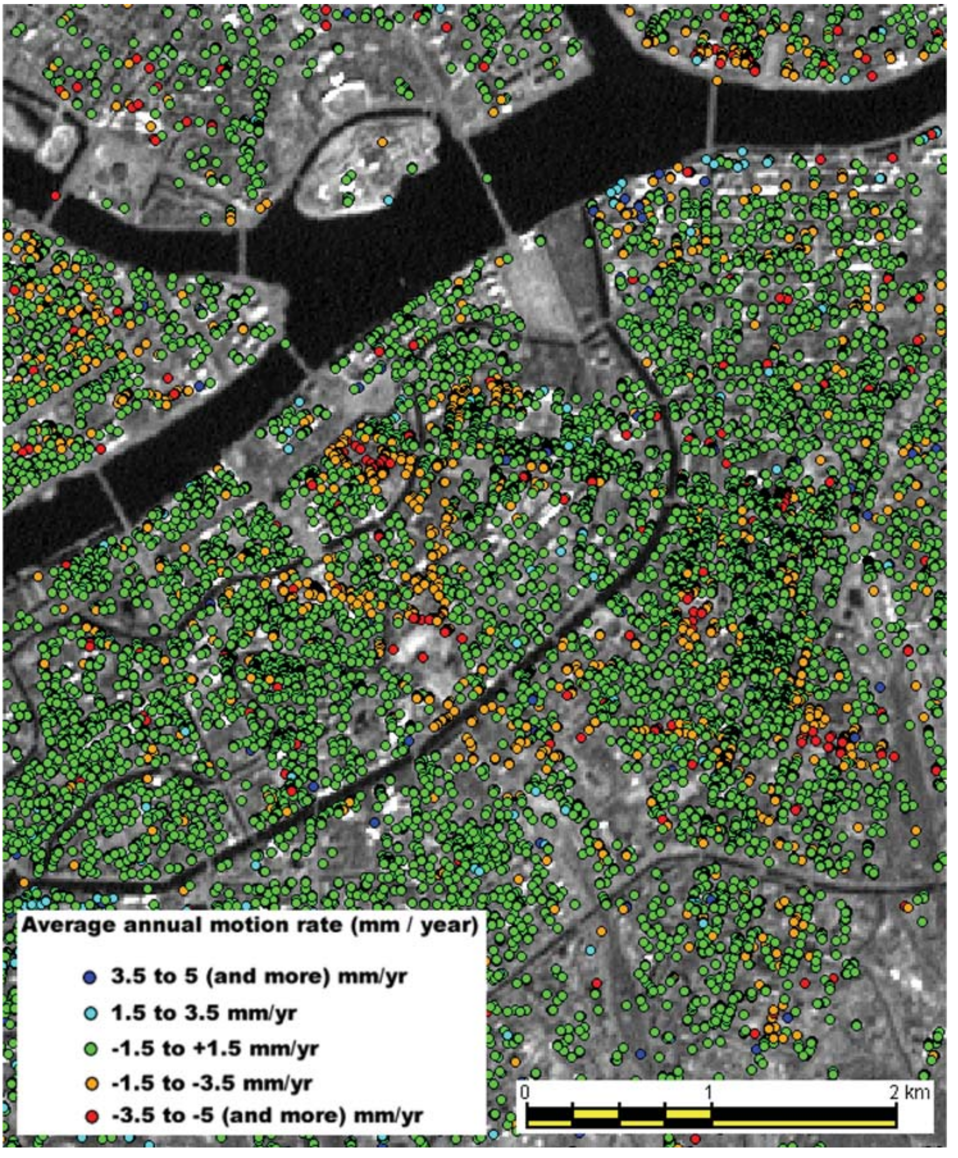

Fig. 3. Map of persistent scatterer points, with their calculated average annual motion rates (mm $year^{-1}$, colour-coded) for St. Petersburg, Russia. PSI data copyright NPA Group 2005; ERS data copyright ESA 1992–2004; background image Landsat ETM + Band 8. (Data processed by NPA for ESA's GMES Terrafirma service.)

(3) water, brine, oil, or gas extraction and underground coal mining: ground subsidence measurements during extraction (Usai 1997);

(4) ice motion: mapping the motion of glaciers, ice streams, ice sheets (Goldstein *et al.* 1993).

An example for earthquakes is given in Figure 2, which shows an 'interferogram' or deformation map, generated after the Izmit (Turkey) magnitude of 7.4 earthquake on 17 August 1999. ERS SAR images from 13 August 1999 and 17 September 1999 were used to generate this map. Each fringe cycle corresponds to a specific amount of relative motion in the LOS of the satellite. This amount is a function of the radar wavelength; in this case each cycle represents 28 mm of motion. A total of 4 m displacement in the satellite's LOS was measured. Further information on the use of DifSAR with the Izmit earthquake is available from Wright *et al.* (2001).

Persistent scatterer interferometry (PSI)

The PSI technique was first introduced by Ferretti *et al.* (1999) and different algorithms have been developed since then (e.g. Werner *et al.* 2003). PSI uses about 30–100 co-registered SAR images to identify time-persistent radar scatterer points and to derive an atmospheric phase screen for each scene. Correction for atmospheric effects produces much finer measurements than the DifSAR technique. For each one of these persistent scatterers, a motion history is available for the time span of the available data, which could stretch back to 1992 using combined ERS-1, ERS-2 and Envisat data.

PSI maps wide-area relative ground movements with sub-centimetric precision along the satellite's LOS and its vertical precision is beyond that achievable with the Global Positioning System (GPS). Using ERS data, the absolute spatial accuracy is about 15 m, and the relative spatial accuracy is about ± 5 m in east–west and ± 2 m in north–south direction. 'Spatial accuracy' refers in this context to the accuracy of locating the persistent scatterer on the ground. PSI represents a rapid and cost-effective measure of ground motion: over large areas with built infrastructure; in areas undergoing slow and steady subsidence (smaller than 10 cm year^{-1}); for long measurement periods (>5 years).

Urban areas are best suited as PSI application areas, and Figure 3 shows an example of PSI output for St. Petersburg, giving the average annual motion rate of ground points for the period between 1992 and 2004. For every persistent scatterer shown in Figure 3, an individual time series is available (see Fig. 4).

It should be noted that it is the movement of the persistent scatterer (e.g. a building) that is measured and not that of the ground (although in many instances these will be interrelated). Furthermore, for ground motion to be resolved unambiguously in the resulting PSI maps, ground movement between two SAR acquisitions (in the range of 24–35 days for the current missions Radarsat-1 and ERS-2–ENVISAT, respectively) should not exceed a quarter of the wavelength of the sensor. For example, for ERS with a wavelength of 5.6 cm, subsidence rates should not be larger than 1.4 cm per shortest consecutive repeat image acquisition (35 days).

PSI requires a large number of ERS SAR scenes (minimum 30 but ideally as many as are available). A feature of the technique is that the number and location of persistent scatterers cannot be predicted before processing, and measurement success can be guaranteed only over built-up urban areas or over dry and rocky regions. To complement the

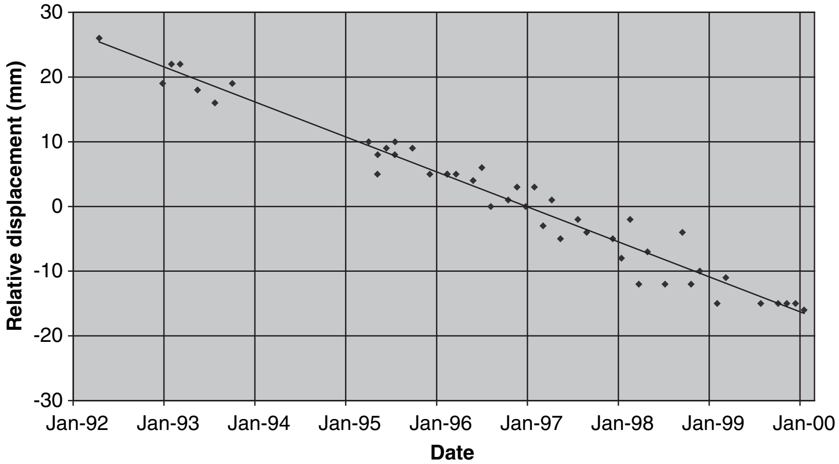

Fig. 4. Example time series of ground displacement of a single persistent scatterer. The displacement values are relative to a chosen reference point.

Fig. 5. A metallic Corner Reflector (CR), with a Compact Active Transponder (CAT) in the foreground.

distribution of persistent scatterer points, artificial radar reflectors can be installed at locations of interest.

Corner Reflectors and Compact Active Transponders

Corner Reflectors (CRs) are purpose-built triangular reflecting metal plates angled upwards towards the satellite and installed at specific locations of interest (see Fig. 5). The size of the CR is less than 1.2 m in all three dimensions and attaches to a flat base-plate, which is anchored into the ground, by concreting and/or ground spikes. Sub-centimetric ground movements are detectable at each CR location. The absolute spatial accuracy is about 20 m for the current Radarsat-1 and Envisat missions, but can be precisely ascertained at the time of installation by GPS surveying. To receive a clear CR response,

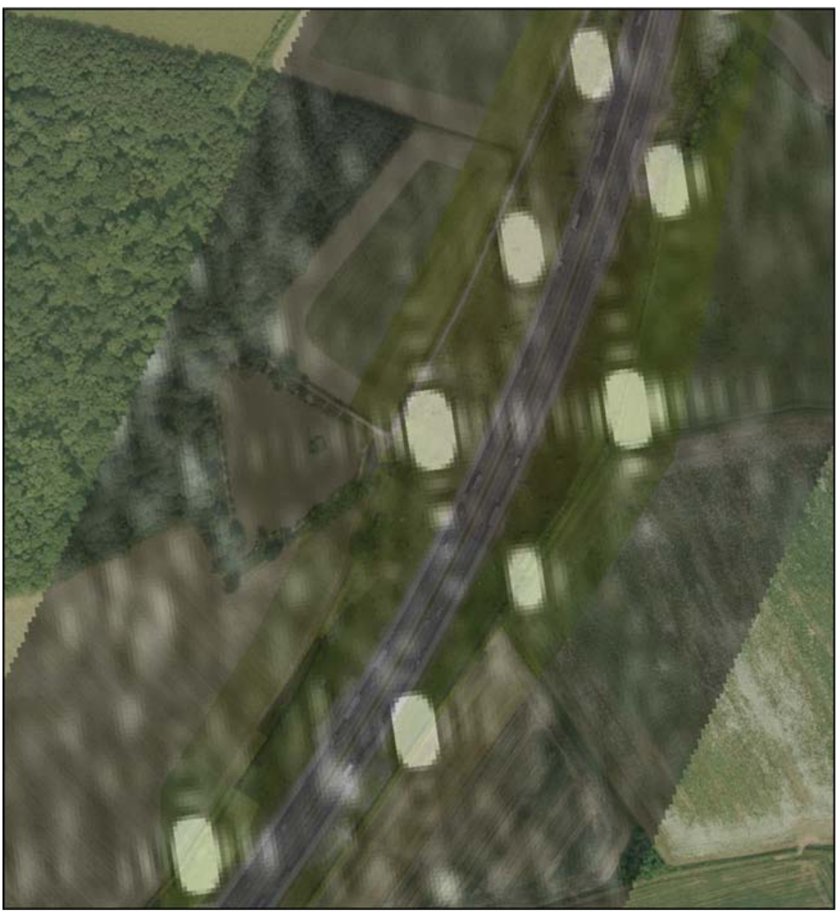

Fig. 6. Intensity responses from a network of NPA's Compact Active Transponders, deployed for monitoring subsidence with InSAR. Image copyright NPA Group 2005.

CRs need to be sited away from other potential scatterers such as buildings or metallic structures, or overhead obstructions. CRs may be used to map slow landslip or structural instability (e.g. dams, bridges) with sub-centimetric precision in height. Operability is best in remote areas, where the CRs are not subjected to vandalism.

An alternative to CRs are Compact Active Transponders (CATs; see Fig. 5), which are more compact than CRs and do not suffer as much from environmental impact such as strong winds and the accumulation of debris or snow. Whereas CRs can only be oriented to suit either the ascending or descending viewing modes of the satellite (i.e. when orbiting south to north or north to south, respectively), CATs can be used for the two modes in one setup, and are responsive to all line-of-sight modes of radar satellites.

Figure 6 shows the radar responses from part of a network of NPA transponders (CATs) deployed in a region of subsidence. The transponders are *c.* 150 m apart and their intensity responses in the radar imagery are overlaid on optical data. Through InSAR analysis of their SAR phase component, motion at these locations can be measured and monitored over time.

Summary

Within a decade, imaging radar interferometry has matured into a widely used geodetic technique for measuring the topography and deformation of the Earth. There are three relative ground motion measurement techniques that complement each other for monitoring geohazards: (1) differential interferometry to map wide-area movements at low cost; (2) persistent scatterer interferometry to provide a time series (dating back to 1992) of ground movement for each persistent radar reflector found in the scene; (3) Corner Reflector and Compact Active Transponder interferometry to measure ground motion at specific locations.

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