Surface Deformation Related to the 2019 $M_w$ 7.1 and 6.4 Ridgecrest Earthquakes in California from GPS, SAR Interferometry, and SAR Pixel Offsets

Eric Jameson Fielding*1, Zhen Liu1, Oliver L. Stephenson2, Minyan Zhong2, Cunren Liang2, Angelyn Moore1, Sang-Ho Yun1, and Mark Simons2

Abstract

We analyzed Synthetic Aperture Radar (SAR) images from Copernicus Sentinel-1A and 1B satellites operated by the European Space Agency and the Advanced Land Observation Satellite-2 (ALOS-2) satellite operated by the Japan Aerospace Exploration Agency and Global Navigation Satellite System (GNSS) data from the Network of the Americas for the 4 July 2019 $M_w$ 6.4 and 5 July (local; 6 July UTC) $M_w$ 7.1 Ridgecrest earthquakes. We integrated geodetic measurements for the 3D vector field of coseismic surface deformation for the two events, using SAR data from Sentinel-1 and ALOS-2 satellites. We combined less precise large-scale displacements from SAR images by pixel offset tracking or matching, with the more precise SAR interferometry (Interferometric Synthetic Aperture Radar [InSAR]) measurements in the radar line of sight (LoS) direction and intermediate-precision along-track InSAR to estimate all three components of the surface displacement for the two events together. We also estimated the coseismic deformation for the two earthquakes from time-series processing of continuous Global Navigation Satellite System data stations in the area. InSAR coherence and coherence change maps the surface disruptions due to fault ruptures reaching the surface. Large slip in the $M_w$ 6.4 earthquake was on a NE-striking fault that intersects with the NW-striking fault that was the main rupture in the $M_w$ 7.1 earthquake. The main fault bifurcates towards the southeast ending 3 km from the Garlock Fault. The Garlock fault had triggered slip of about 20 mm in the radar LoS along a short section directly south of the main rupture. About 3 km northwest of the $M_w$ 7.1 epicenter, the surface fault separates into two strands that form a pull-apart with about 1 m of down-drop. Further northwest is a wide zone of complex deformation.

Introduction

The 4 July 2019 $M_w$ 6.4 and 5 July (local; 6 July UTC) $M_w$ 7.1 Ridgecrest earthquakes ruptured faults and deformed the crust in eastern California. We analyzed Synthetic Aperture Radar (SAR) data acquired by the Copernicus Sentinel-1 and Japan Aerospace Exploration Agency (JAXA) Advanced Land Observation Satellite-2 (ALOS-2) satellites and continuous Global Navigation Satellite System (GNSS) data from permanent stations of the Network of the Americas (previously called the Plate Boundary Observatory) to map the coseismic surface deformation in the region around Ridgecrest related to the earthquakes. A subset of preliminary versions of these results was used to estimate an early coseismic slip model (Ross et al., 2019), and here we present a more complete description of the data products for others to use. Several of the data products have been improved. We combined measurements from the SAR data that are sensitive to different components of the surface deformation to estimate the 3D surface deformation field. This 3D surface deformation field is useful for estimating static coseismic slip distribution on model faults. Other coseismic slip distributions have been published as of the time of this writing (Barnhart et al., 2019; Goldberg et al., 2019; Liu et al., 2019) using other geodetic measurements.

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Experiment Design

The SAR data presented here were processed from three satellites (see Table 1). The Copernicus Sentinel-1A and Sentinel-1B satellites are operated by the European Space Agency (ESA) for the European Union Copernicus program. The ALOS-2 satellite is owned and operated by JAXA. All three satellites acquire data toward the right side of the satellite orbital motion. The two identical Sentinel-1 satellites are in the same orbital plane, with a 180° phase separation. The time between orbit repeats for one satellite is 12 days, and when both the two satellites are acquiring data, the interval is six days. The SAR data we used were acquired in the Terrain Observation by Progressive Scans (TOPS) mode, also called interferometric wide-swath, which is processed to a SAR image with a posting or pixel spacing of about 2.3 m in the slant range (distance across the swath measured along the line of sight [LoS]) direction and 14 m in the along-track direction. The swath width is 250 km. The radar wavelength is 5.547 cm, called C-band. The two tracks covering the Ridgecrest area are ascending (satellite moving north) track 64 and descending (satellite moving south) track 71. The coverage of the Sentinel-1 scenes is shown in Figure 1.

The ALOS-2 satellite has an orbit with a 14-day repeat interval, and it uses a radar with a 24.2 cm wavelength, called L-band. JAXA operates the ALOS-2 SAR system in several different modes at different times. All of the postearthquake scenes were acquired with the wide-swath ScanSAR WD1 mode beam number W2. The ALOS-2 ScanSAR W2 beam has a 350 km swath width and an approximate resolution of 20 m in the across-track (ground range) direction and 50 m in the along-track direction. One of the prequake ALOS-2 scenes was acquired with the stripmap SM3 mode, which has roughly 10 m resolution in the across-track (ground range) direction and 5 m resolution in the along-track direction, but has a much narrower 70 km swath width. The coverage of the ALOS-2 scenes is also shown in Figure 1.

Geodetic observations from GNSS stations in the Network of the Americas (NOTA), operated by UNAVCO, are used to estimate accumulated coseismic displacements for the 4–5 July 2019 Ridgecrest earthquake sequence. The stations within 500 km of the earthquake epicenters are used in the analysis (see Fig. 2).

Data Processing

We analyzed the SAR data with three different methods to extract as much information about the ground deformation as possible. The methods measure surface displacements in the LoS direction and in the horizontal direction parallel to the satellite track (flight direction). The Sentinel-1 SAR images were processed with the Jet Propulsion Laboratory (JPL) Interferometric Synthetic Aperture Radar (InSAR) Scientific Computing Center.

<table>
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<th>SAR Timing</th>
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Asc., ascending track; A2, Advanced Land Observation Satellite-2 (ALOS-2); Des., descending track; SAR, Synthetic Aperture Radar; S1A, Sentinel-1A; S1B, Sentinel-1B. Dates are UTC dates.
Environment (ISCE) v.2 software (Rosen et al., 2012) “topsApp.py” application, starting from the Level 1 data products from ESA, called single-look complex (SLC) data. The SLC images before and after the earthquake are precisely coregistered using the orbit data and topographic data from the Shuttle Topography Radar Mission (Farr et al., 2007). Then, we performed both the regular interferometric processing to make interferograms and coherence maps, and pixel offset tracking on the SLC images. We used only the orbits and frequency modulation rate corrections for coregistering the images and did not apply the enhanced spectral diversity empirical estimate of residual along-track shifts. The Sentinel-1 interferograms were corrected for ionospheric effects on the interferogram phase by performing split-spectrum analysis of the SAR data (Liang et al., 2019), including the estimated along-track shifts. The regular interferograms measure the difference in distance (range) between the satellite and the ground along the LoS. The interferogram processing was done at approximately 30 m pixel size, see Table 2 for details of numbers of looks or pixels averaged in range and azimuth directions. Averaging was done before filtering and unwrapping. We manually created masks to remove the interferogram data close to the two main fault ruptures to enable more accurate phase unwrapping. The masks were chosen to follow the main ruptures and mask out areas of complex surficial deformation in Searles Lake. Unwrapped phase, including the masked areas set to no-data, was then resampled to 3 arcsec (∼90 m; 0.000833333°) spacing for the final products.

We also applied pixel offset tracking analysis to the Sentinel-1 SLC images on both tracks, sometimes called sub-pixel correlation. This analysis does cross correlation between the SAR amplitude images, after the geometric coregistration with ISCE described earlier, to measure the image distortion or offsets as a fraction of the pixel size due to the earthquake in the SAR imaging plane, which is the radar LoS (slant range) direction and the along-track (azimuth) direction parallel to

Table 2

<table>
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<td>SAR pixel offsets</td>
<td>64‡</td>
<td>16‡</td>
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</table>

A2, Japan Aerospace Exploration Agency (JAXA) ALOS-2; InSAR, Interferometric Synthetic Aperture Radar (range); MAI, multiple-aperture interferometry (along-track); S1, Copernicus Sentinel-1.

*ALOS-2 regular ScanSAR azimuth looks include 14 azimuth looks from full-aperture single-look complex (SLC) processing.
‡ALOS-2 burst ScanSAR azimuth looks from resampled burst SLC.
‡SAR pixel offset looks are size of image matching window.
the satellite motion (Simons et al., 2002; Pathier et al., 2006).
Because the Sentinel-1 SLC images have very different sampling
in the range (2.3 m) and azimuth (14 m) directions, we used a
cross-correlation window or chip that was 64 pixels in range
and 16 pixels in azimuth, or a matching window size about
150 × 220 m in size. The images were oversampled by a factor
of 64 in the matching process to extract offsets with a precision
of 1/64 of a pixel, although the accuracy is not as good due to
noise. To further reduce the noise in the estimated offsets, we
applied a median filter that was 500 m wide to the range and
azimuth displacements. The results were geocoded at a sample
spacing of 0.002° (≈200 m) in latitude and longitude.

We used the SAR pixel offset maps from the two Sentinel-1
tracks to calculate the full 3D surface deformation field. The four
SAR pixel offset components (slant range, in the LoS
direction, and azimuth, in the along-track direction, displace-
ments from both ascending and descending tracks) were com-
bined in a least-squares inversion for the east, north, and up
components of the surface displacement at the same sample
spacing as the geocoded pixel offset maps, 0.002° (≈200 m),
using the vectordisp program (see Data and Resources). The
method is similar to that used by Delbridge et al. (2016) and
Minchew et al. (2017). An advantage of the SAR pixel offsets
compared to pixel offsets from optical satellites is that the SAR
imaging geometry is sensitive to the vertical in addition to the
horizontal with the slant-range measurements; therefore, we
can estimate the vertical component of deformation from the
combination of two SAR tracks.

We processed the ALOS-2 SAR images from the level 1.1
full-aperture SLC products provided by JAXA, using the ISCE
software and some additional modules added for the special
ALOS-2 ScanSAR acquisition modes (Liang and Fielding,
2017a; see Data and Resources). We processed both regular
InSAR in the LoS direction and along-track InSAR, often called
multiple-aperture interferometry (MAI), from the ALOS-2
pairs. On ALOS-2 ascending track 65, the shortest time interval
was covered by a ScanSAR-stripmap pair (see Table 1), which
we processed with range spectrum and multitaper azimuth
spectrum filters to extract the overlapping portions of the range
and azimuth spectra present in both images of the pair (see
Liang and Fielding, 2017a for details). The Ridgecrest area
is arid with very little vegetation, and the L-band interfero-
grams have very high coherence right up to the fault ruptures.
We reduced the amount of spatial averaging to two range and
14 azimuth looks (pixels averaged) and strength of filtering to a
very low level (0.01 exponent, 64 × 64 pixel window size) on the
power-spectrum filter (Goldstein and Werner, 1998) to enhance
the resolution and reduce unwrapping errors. Averaging 14 azi-
muth pixels (14 looks) is necessary for the full-aperture SLC
processing to produce interferogram pixels with the actual
ScanSAR azimuth resolution because the full-aperture SLC is
highly oversampled in azimuth. Averaging was done before
spatial filtering and unwrapping.

For the ALOS-2 pairs on paths A66 and D166, we had to do a
manual masking of the main ruptures from the $M_w$ 6.4 and 7.1
earthquakes to prevent the phase unwrapping program from
connecting the phase across the ruptures, similar to what we
did for the Sentinel-1 interferograms. We estimated ionospheric
corrections for the interferogram phase using the split-spectrum
method (Liang and Fielding, 2017b) and applied the correction
to all the regular (LoS) ALOS-2 interferograms. Unwrapped
phase, with the masked out areas set to no-data, was then geo-
coded and resampled to 3 arcsec (∼90 m; 0.000833333°) spacing.

We also processed several of the ALOS-2 ScanSAR–ScanSAR
pairs to calculate along-track (azimuth) deformation by separat-
ing the original bursts and doing differential interferograms of
forward and backward images of the ground surface (Liang and
Fielding, 2017b), equivalent to the technique called MAI. The
process of extracting the original bursts also resamples the data
in the azimuth direction so that the along-track pixel size is 52 m
on the ground in the burst SLC images. Along-track differential
interferograms have lower accuracy and precision than regular
LoS interferograms, but provide a measurement of horizontal
deforation along the radar track.

We processed daily position time series for the selected set
of GNSS stations using JPL GipsyX software (see Data and
Resources) (W. Bertiger et al., unpublished manuscript, 2019,
see Data and Resources). The JPL final precise Global
Positioning System (GPS) orbits and clock estimated from a
globally distributed network are used in the analysis (Desai et al.,
2011, 2014). For the processing, we employ precise point posi-
tioning (Zumberge et al., 1997) and single receiver phase ambigu-
ity resolution strategy (Bertiger et al., 2010). We employ a
fitting window approach (Liu et al., 2014) to estimate 3D coseis-
mic displacements and one-sigma uncertainties of the earth-
quake sequence, using mean positions of 15 days before the
$M_w$ 6.4 earthquake and three days after the $M_w$ 7.1 earthquake.
Uncertainties are derived from scatter of daily positions before
and after the earthquakes.

Results and Data Quality
As described earlier, we measured the combined surface dis-
placements from the two earthquakes with both the SAR and
GNSS data analysis. The InSAR and SAR pixel offset results are
from SAR image pairs listed in Table 1. Three ALOS-2 tracks,
which JAXA calls paths, and two Sentinel-1 tracks cover the
Ridgecrest area.

The first SAR image acquired after the earthquakes was the
ALOS-2 scene on 8 July (UTC date) on ascending path 65. The
ScanSAR–stripmap pair from 16 April 2018 to 8 July 2019
interferogram is shown in Figure 3a, showing the LoS displac-
ements with the sign convention that toward the satellite (up or
west) is positive that we use for all the LoS products. This
ALOS-2 pair has good quality unwrapping without application
of a manual mask. The same postquake scene was processed
with a prequake ScanSAR scene from 8 August 2016 to
Figure 3. ALOS-2 interferograms for Ridgecrest earthquakes from ascending tracks. Light green stars show $M_w$ 6.4 and 7.1 epicenters (Ross et al., 2019). Areas of low coherence masked out and area outside data are both light gray. (a) Path A65 range or line of sight (LoS) interferogram 16 April 2018–8 July 2019 (ScanSAR–stripmap). (b) Path A65 along-track interferogram 8 August 2016–8 July 2019 (ScanSAR). (c) Path A66 LoS interferogram 12 August 2017–13 July 2019 (ScanSAR). (d) Path A66 along-track interferogram 12 August 2017–13 July 2019 (ScanSAR). Arrows show directions of LoS (ground-to-satellite) or along-track measurement. Overlays show $M_w$ 6.4 and 7.1 epicenters, Quaternary faults (U.S. Geological Survey and California Geological Survey 2018), and preliminary surface ruptures mapped in the field and with imagery (Kendrick et al., 2019, D. Ponti et al., unpublished manuscript, 2020, see Data and Resources). See Figure 4b for full legend of surface ruptures. The color version of this figure is available only in the electronic edition.
calculate the along-track interferogram shown in Figure 3b. The along-track measurement is positive in the direction of the satellite track (about 12° west of north for this track). Because of the longer time interval, the coherence is lower for the regular interferograms and along-track differential interferograms for this pair than the 2018–2019 pair, and the resulting along-track measurements are noisy. Areas of very low coherence could not be unwrapped and are masked out. There are some small ionospheric effects in this along-track interferogram, but they are smaller than the main earthquake signal so the interferogram is still usable for modeling.

We processed ALOS-2 data from another ascending track, path 66, for both regular and along-track interferograms with ScanSAR–ScanSAR pairs (Fig. 3c,d). The available data are from 13 August 2016, 12 August 2017, and 13 July 2019. We only show the 2017–2019 pair interferograms as the longer interval of the 2016–2019 pair results in lower quality. The 2017–2019 regular ScanSAR–ScanSAR LoS interferogram on this track (Fig. 3c) has somewhat lower coherence than the 2018–2019 ScanSAR–stripmap interferogram from path A65. We had to use a manual mask of the fault ruptures to aid the unwrapping. The LoS angle for this track is further from the vertical than for path A65, so it is more sensitive to horizontal displacements, although the horizontal projection of the LoS vector is almost the same. Our along-track differential interferograms from this track, using both the

Figure 4. (a) ALOS-2 coseismic LoS interferogram from path D166 for same area as Figure 3, acquired 2 April 2019–23 July 2019. Areas of low coherence and near-main ruptures masked out (gray). Overlays show $M_w$ 6.4 and 7.1 epicenters, Quaternary faults (U.S. Geological Survey and California Geological Survey 2018), and preliminary surface ruptures mapped in the field and with imagery (Kendrick et al., 2019; D. Ponti et al., unpublished manuscript, 2020, see Data and Resources). Arrow shows LoS horizontal direction. (b) Legend of different colors of Ridgecrest surface rupture lines indicate mapping source (see D. Ponti et al., unpublished manuscript, 2020, see Data and Resources for more details) used for Figures 3–8. The color version of this figure is available only in the electronic edition.
2016–2019 and 2017–2019 pairs are relatively coherent, but have strong contamination from the ionospheric variations in a set of west-northwest–east-southeast-trending waves with an amplitude greater than 1 m of along-track displacement (Fig. 3d). Because the ionospheric effects are similar in both pairs, we conclude that the strong ionospheric waves are in the 13 July 2019 acquisition. The small spatial wavelength of the ionospheric ripples means that we cannot successfully estimate and remove the effects with the split-spectrum method from the along-track interferograms due to the small range bandwidth (14 MHz) of the ALOS-2 ScanSAR data and the fact that along-track ionospheric effects are proportional to the gradient of the ionospheric delay difference. The LoS interferogram effects are proportional to the difference in the ionospheric delay on the two dates, which is what we measure with the split-spectrum method, so the ionospheric corrections on the LoS phase are successful.

We processed ALOS-2 ScanSAR data from the descending track that covers Ridgecrest, path 166, with data acquired on 2 April 2019 and 23 July 2019. The regular LoS interferogram is shown in Figure 4. As with the ascending ALOS-2 tracks, we used a small number of looks (spatial averaging) and low-spatial smoothing to enhance the resolution and phase unwrapping, and we performed the ionospheric correction. For this pair, we also used a manual mask of the phase along the main ruptures to reduce unwrapping errors. The different LoS direction on this descending track shows a very different pattern from the ascending tracks because horizontal and vertical motions project differently.

Two Copernicus Sentinel-1 standard interferometric wide-swaths cover the Ridgecrest area (see Fig. 1). Both tracks had images acquired on 4 July 2019 (UTC), approximately 15 hr and 3 hr before the $M_w$ 6.4 earthquake. The first Sentinel-1 image acquired after the earthquakes was along ascending track 64 on 10 July 2019, which enabled the calculation of a six-day interferogram (Fig. 5). Similar to the ALOS-2 interferograms, we found it was necessary to add a manual mask of the phase along the major ruptures to reduce the unwrapping errors. The short-time interval in this arid area enables very high coherence, except in the region close to the main $M_w$ 7.1 rupture where there is significant disruption or high-deformation gradients that cause low coherence or fringes that are not possible to unwrap. Those areas are masked out in our unwrapped interferogram product. We applied the ionospheric correction to the phase, but the ionospheric estimate was relatively small, as is common at middle latitudes. After the ionospheric correction, the burst discontinuities far from the earthquake deformation were removed, but discontinuities near the main ruptures remained. The deformation due to the $M_w$ 7.1 earthquake in the along-track direction.

Figure 5. Coseismic LoS deformation from Sentinel-1 A/B interferogram on track 64, acquired on 4 July 2019 and 10 July 2019. Other symbols are same as in Figure 4. The color version of this figure is available only in the electronic edition.
causes substantial phase discontinuities due to the large difference in Doppler centroid in the burst overlap region (Grandin et al., 2016; Liang et al., 2019).

For the Copernicus Sentinel-1 descending track 71, we processed the coseismic 12-day pair, with similar very high coherence away from the fault ruptures (Fig. 6). Again, we applied the ionospheric correction to the phase, and we found that the corrections were small. We applied a similar manual mask of the main ruptures and the highly disrupted Searles Lake to aid the phase unwrapping. There are also phase discontinuities near the main rupture due to the large ground displacements in the along-track direction in this coseismic interferogram.

We processed both Sentinel-1 tracks with pixel offset tracking (image cross correlation) on the six-day and 12-day SLC image pairs after geometric coregistration. The quality of the image correlation was high over the whole area, except over parts of Searles Lake where there was significant surface disruption. The pixel offsets were converted to displacements in meters in the SAR image plane: slant range or cross-track distance from ground to satellite and azimuth or along-track directions (Fig. 7). As expected, the accuracy and precision of the along-track measurements in meters (Fig. 7b,d) is about six times worse than the measurements in the slant-range direction (Fig. 7a,c) due to the much larger pixel size (14 vs. 2.3 m). One big advantage of the SAR pixel offsets over InSAR measurements is the ability to measure large displacements without saturation or phase unwrapping errors. The SAR pixel offsets are also not as sensitive to small-scale disruption of the surface as InSAR because the image matching window is about 200 m across. On the other hand, the pixel offsets have much coarser resolution and lower accuracy on the order of 1/20 of the pixel size. We are able to calculate along-track pixel offsets from Sentinel-1 TOPS images that cannot be used for complete along-track interferometry due to the TOPS mode, and we are able to measure LoS displacements that are too large to measure with InSAR. The along-track pixel offsets show that the greatest amount of slip on the \( M_w 7.1 \) rupture is very close to the epicenter.

We used the four components of SAR pixel offsets from the two Sentinel-1 tracks (A64 and D71, range and azimuth offsets) to calculate the 3D coseismic surface displacements: east, north, and up (Fig. 8a–c). The east and up components are primarily controlled by the range offsets, so they have better accuracy than the north component that is primarily from the along-track offsets. The 3D displacements may be easier for modeling than the original SAR pixel offsets, and the SAR pixel offsets are stable at

Figure 6. Coseismic LoS deformation from Sentinel-1 interferogram on descending track 71, acquired on 4 July 2019 and 16 July 2019. Areas of low coherence, including Searles Lake, and region near-main rupture masked out (gray). Arrow shows LoS direction. Other symbols are same as in Figure 4. The color version of this figure is available only in the electronic edition.
large spatial scales due to the high stability of the Sentinel-1 satellites and the SAR image formation process. There is a difference in the time interval between A64 (six days; 4–10 July) and D71 (12 days; 4–16 July), but we know that the postseismic deformation during the six days from 10 to 16 July is much smaller than the coseismic deformation (maximum of 2 cm), which we confirmed with a postseismic interferogram on track A64 (not shown here). The east and north components of the displacement can be used to calculate horizontal displacements in any other direction. For example, we calculated the displacement perpendicular to the main $M_w$ 7.1 rupture and roughly parallel to the $M_w$ 6.4 rupture along the N65°E direction (Fig. 8d). This shows motion perpendicular to the main $M_w$ 7.1 rupture, including the $M_w$ 6.4 rupture and the large-scale motion westward to the west of the

Figure 7. Coseismic pixel offset maps from Sentinel-1 pairs. (a) Ascending track 64 range (LoS) direction, (b) track 64 azimuth (along track) direction, (c) descending track 71 LoS direction, (d) track 71 along-track direction. Arrows show LoS or track direction. Other symbols are same as in Figure 4. The color version of this figure is available only in the electronic edition.
north end and eastward to the east of the south end of the $M_w 7.1$ rupture, as expected for a strike-slip earthquake. The vertical deformation (Fig. 8c) shows that there was a block that dropped down up to 1.5 m in an extensional stepover structure about 4 km north of the $M_w 7.1$ epicenter. The block is about 5 km long by 1.5 km wide, with the largest vertical displacements on the north-east side.

The GNSS coseismic displacements east, north, up components, and associated uncertainties are listed in Table S1 (see supplemental material), and the horizontal displacements are shown in Figure 2. The largest displacement is at station P595, which moved more than 66 cm to the southeast during the two earthquakes. The Goldstone area of the National Aeronautics and Space Administration (NASA) Deep Space Network antennas moved about 3.8 cm to the southeast (station GOLD and others). All but the most distant stations had coseismic displacements above the estimated one-sigma uncertainties.
listed in Table S1. A few stations had large uncertainties and anomalous offsets, including station TIVA in Nevada.

Data and Resources

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