SANDIA REPORT
SAND2022-13587
Printed October 2022

Sandia National Laboratories

Synthetic Aperture Radar Image Geolocation Using Fiducial Images

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Synthetic Aperture Radar Image Geolocation Using Fiducial Images

Armin W Doerry and Douglas L Bickel

Abstract

Synthetic Aperture Radar (SAR) creates imagery of the earth's surface from airborne or spaceborne radar platforms. However, the nature of any radar is to geolocate its echo data, i.e., SAR images, relative to its own measured radar location. Acceptable accuracy and precision of such geolocation can be quite difficult to achieve, and is limited by any number of parameters. However, databases of geolocated earth imagery do exist, often using other imaging modalities, with Google Earth being one such example. These can often be much more accurate than what might be achievable by the radar itself. Consequently, SAR images may be aligned to some higher accuracy database, thereby improving the geolocation of features in the SAR image. Examples offer anecdotal evidence of the viability of such an approach.

Acknowledgements

This report is the result of an unfunded Research and Development effort.

A special thank you to Tommy Burks for his data collections in the Albuquerque area.

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Acronyms and Definitions

1-D, 2-D, 3-D	One-, Two-, Three-Dimensional
AFB	Air Force Base
DoD	[US] Department of Defense
GEOINT	Geospatial Intelligence
GIS	Global Information System
GNSS	Global Navigation Satellite System
HAE	Height Above Ellipsoid
IGS	International GNSS Service
ISR	Intelligence, Surveillance, and Reconnaissance
LIDAR	Light Detection and Ranging
MSL	Mean Sea Level
NGA	National Geospatial-Intelligence Agency
RMS	Root Mean Squared
RMSE	Root Mean Squared Error
SAR	Synthetic Aperture Radar
SIG	Single Image Geolocation
SRP	Scene Reference Point
USGS	United States Geological Service

Foreword

This report details the results of an academic study. It does not presently exemplify any modes, methodologies, or techniques employed by any operational system known to the authors.

Classification

The specific mathematics and algorithms presented herein do not bear any release restrictions or distribution limitations.

This report formalizes preexisting informal notes and other documentation on the subject matter herein.

This report has been approved as Unclassified – Unlimited Release.

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1 Introduction and Background

Synthetic Aperture Radar (SAR) is a technique for making images or maps of the radar reflectivity of some surface, quite often the earth. Resolution of the images is typically much finer than the area illuminated by the radar's antenna beam footprint. These images often look like monochromatic aerial photographs, but upon closer inspection exhibit phenomenology that is significantly different. Nevertheless, SAR images are used in a variety of applications, including resource monitoring, feature mapping, and Intelligence, Surveillance, and Reconnaissance (ISR) missions.

In any case, having an image can be a good thing, but knowing where the image is and relating its features to their geolocations is even better; much better.

Radar inherently measures geometric quantities with respect to its own position, i.e., referenced to the radar's own location. Several geolocation techniques have been described in earlier reports, and even more are discussed in the public literature. To be sure, these can be quite accurate, but ultimately depend on the accuracy and precision of the radar's own navigation instrumentation and proper assessment of propagation characteristics.[1,2,3] A truism is that accuracy generally gets worse with range.

We note however, that other references for geolocation might be employed other than the radar's own measured location. For example, we might use fiducial markers or tie points in the image itself, or even fiducial images from other technologies, techniques, and databases thereof.

> Definition: fiducial
> (adjective) trusted as a fixed basis for reference or comparison.
> (noun) an object or feature that serves as a fixed basis for reference or comparison.

In this report we discuss geolocating features in a SAR image based on comparing the SAR image to a fiducial image (itself not necessarily a SAR image) which has been previously geolocated. We stipulate that this idea is neither novel nor complicated. We seek herein simply to discuss and demonstrate the utility of this approach. In some circles, this might be termed "knowledge aiding" of our geolocation task.

Section 2 discusses the basic process of geolocating a SAR image feature using a fiducial image. It discusses specifically using the Google Earth database as the fiducial image, although other references are also mentioned. Source publications of image alignment techniques are mentioned. Finally, a brief qualitative discussion of errors is presented.

Section 3 provides a pair of examples that illustrate the geolocation improvement that might be had.

Section 4 provides some concluding remarks.

"First you get the feeling, then you figure out why."
— *Robert M. Pirsig, Zen and the Art of Motorcycle Maintenance*

2 Discussion

Essentially, the process is as follows,

1. Collect and form a SAR image,
2. Align the SAR image to another fiducial image or map that has already been geolocated. This essentially transfer-aligns the SAR image from the fiducial image or map.
3. Determine the geolocation of the feature of interest in the newly aligned SAR image.

Ultimately, the utility of this approach depends on the 'goodness' of the fiducial image, and how well we can align to it.

2.1 Existing Fiducial Imagery

Several databases of fiducial images are available to us. Because of its ubiquity, popularity, and ease of use, we will focus our attention on Google Earth.[4]

2.1.1 Google Earth

Google Earth is a Global Information System (GIS) application software package that renders geolocated optical imagery based primarily on satellite images. Data sources include NOAA, US Navy, NGA, GEBCO, IBCAO, Landsat, Copernicus, and others.

Locations are detailed with Latitude, longitude, and elevation above Mean Sea Level (MSL).

The precision of latitude and longitude estimates is given at 10^{-6} degrees, which translates to about 11 cm in mid latitudes. Precision in elevation is about 1 m. Accuracy is another story.

The accuracy of Google Earth location coordinate estimates varies greatly from region to region. It has been studied by several researchers. These include the following.

> Pulighe, et al.,[5] report that very high resolution images in the city of Rome, Italy, "have an overall positional accuracy close to 1 m."
>
> Potere[6] reports that "The overall accuracy of the full sample (436 control points) is 39.7 meters RMSE, with a range of 0.4 to 171.6 meters."
>
> Wang and Wang[7] report that an analysis of 757 world-wide International GNSS Service (IGS) reference stations measured an average horizontal position error of 4.38 m. The maximum error was 57 m. They conclude that "The accuracy in China region is about 1.5~2 meters and it's up to 1 meter in the cities of the United States, Europe and Japan."
>
> Ragheb and Ragab[8] report that "Horizontal positional accuracy of online Google Earth imagery for a certain study area located in Cairo varies between 5.89 m and 15.68 m, with RMS value of 10.58 m."

Anecdotally, in Albuquerque, New Mexico, USA, at the time of this writing, we measure the apparent horizontal accuracy of the latest Google Earth coordinates, from 4 October 2020, at almost 1 m. Google Earth images from 25 February 2018 used later in our examples show a similar positional accuracy of slightly less than 1 m. Vertical accuracy is a little harder to judge, but appears to be on the same order as horizontal accuracy. We do note that other historical Google Earth images of this area do not always exhibit the same degree of accuracy, often with errors on the order of several meters or more. Furthermore, even imagery from nominally the same date may not always be mosaicked without errors. For example, one might occasionally find jumps and other discontinuities observed in roads and other features, e.g., Figure 1.

2.1.2 Other

While for this report we will limit ourselves to using Google Earth as a reference, we nevertheless feel compelled to at least list several other roughly comparable commercial reference image data sources, without comment. These might include

- ArcGIS Explorer
- Bing maps
- Bhuvan
- Earth3D
- EarthBrowser
- MapJack
- Marble
- NASA World Wind
- NORC
- OpenWebGlobe
- USGS Map Viewer
- WorldWide Telescope

We have made no effort to be complete, and apologize if your favorite one isn't listed here.

We mention also that many of the states in the USA have ongoing Light Detection and Ranging (LIDAR) mapping programs. We stipulate that care must be taken on many maps because we find that often surface features are removed to map the underlying topography. For example, high-resolution United States Geological Service (USGS) maps are derived from LIDAR data.

We would also be remiss in not mentioning that within the US Department of Defense (DoD) is the National Geospatial-Intelligence Agency (NGA), who is responsible for collecting, analyzing, and distributing geospatial intelligence (GEOINT) in support of national security. It would not be unreasonable to expect that this community has its own databases and tools.[†]

[†] See the NGA web site at https://earth-info.nga.mil/

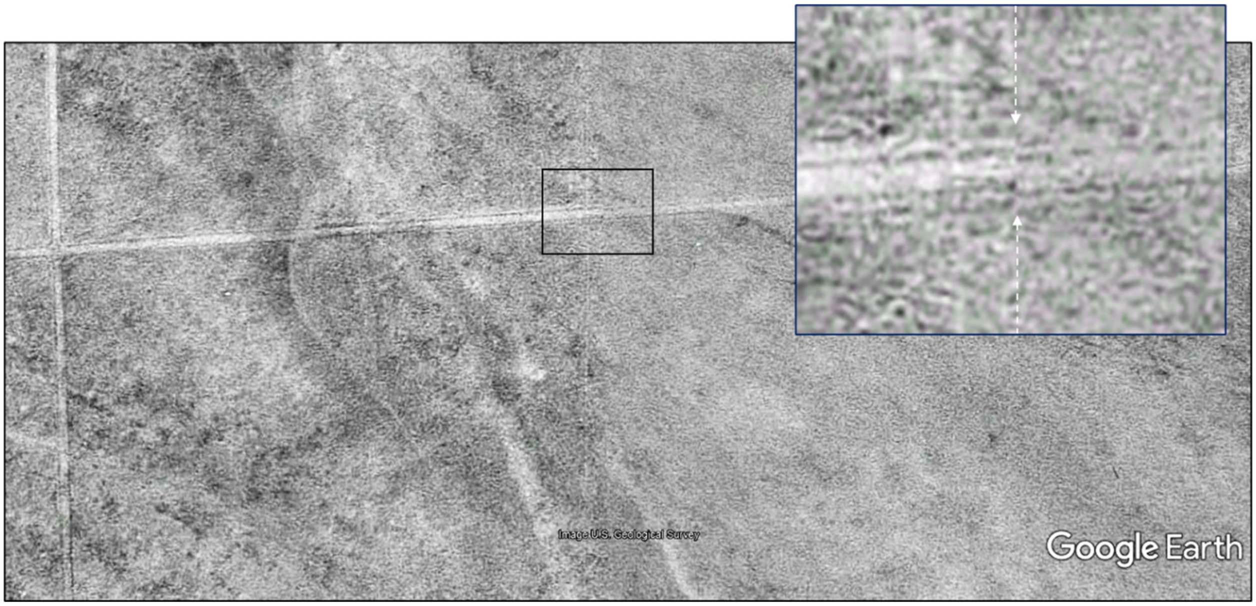

Figure 1. Google Earth historical image from 4 May 1991 exhibiting discontinuity in mosaicking. Feature location is 34.444998 N, -106.557883 E.

2.2 Image Alignment

With a fiducial image database identified, a critical function then becomes to align the SAR image with a reference fiducial image. The idea is to move and warp the SAR image to overlay onto the fiducial reference to match corresponding feature locations, minimizing any corresponding feature location difference. We expect this to generally be a difficult task, especially since the SAR image is a radar image, and the fiducial reference image may be an optical image, or something else.

Image alignment can be a manual operation, relying on the satisfaction of a human operator, or it might be automated and performed by a software implementation of some algorithm.

Machine alignment of seemingly disparate images of generally the same scene has been a long-time area of research. Advocating any specific technique for doing so is beyond the scope of this report, so we offer reference to several representative publications that might detail techniques and algorithms for doing this. These include the following.

Kai and Xueqing[9] provide a good overview and summary of several classes of methods to register SAR images to optical images. Dalmiya and Dharun[10] provide a similar survey of techniques. Both papers have extensive reference lists.

Edges and especially linear features offer particularly good features with which to register SAR images to optical images.[11,12,13,14]

Mutual Information has been proposed by several researchers to register images from different sensor types.[15,16,17]

A literature search on "registering Optical to SAR images" will show that there are many more.

2.3 Error Sources

As with any endeavor, we need to contend ourselves with several areas of imperfection. These manifest as errors in our data and results. Two main categories of errors are

1. Errors in our fiducial image
2. Errors in alignment of our SAR image with the fiducial image

We discuss these in turn.

2.3.1 Fiducial Errors

Our fiducial image is presumed to be "truth" against which the SAR image is aligned. However, we must necessarily ask "Just how truthful is our reference image?"

We must remain mindful that any image is a 2-D projection of a 3-D world. Although tools such as Google Earth present earth imagery as plan views, i.e., overhead perspectives, the images are often taken at somewhat oblique angles. While Google Earth sometimes corrects for this, it often does not. This is evident when examining structures with strong vertical components like utility poles, and sides of buildings. The net result is some degree of "layover," where a vertical offset couples into a horizontal position offset.

Image elevation data is often derived from additional sources, like perhaps the Shuttle Radar Terrain Mapping (SRTM) mission,[18] which provides elevation data for some coarse spatial sample spacing, often called "post spacing." For SRTM data this might be a post spacing of 90 m in most areas, but with an improved 30 m post spacing in some subset areas.[19] Locations between the posts are interpolated. Even so, many smaller scale features of scene topography simply don't manifest in this data.

These error sources, among others, contribute to position and elevation errors in the fiducial images to which the SAR image is aligned. We refer the reader to the previous discussion in section 2.1.1 to note that for Google Earth, the errors can at times be quite large.

Nevertheless, if the fiducial image is of a flat horizontal scene, then we may reasonably expect the fiducial image error for something like Google Earth to be relatively constant over the region of the SAR image. Did we mention that this is for a flat horizontal scene?

2.3.2 Alignment Errors

Even if we may presume to have a "perfect" fiducial image, i.e., with no aberrations or distortions, then we might reasonably ask "How well can we align a SAR image to it?"

First, we must consider some of the distortions inherent in the SAR images. For example, many SAR images are pixelated on a range-Doppler grid, rather than a Cartesian grid. Furthermore, for scenes that aren't horizontally flat, SAR images exhibit layover, which couples an elevation offset into a horizontal position offset, i.e., an error.

Consequently, aligning a SAR image to a reference fiducial image of any kind might require more than just rotation and translation of the SAR image. We might require scaling in either or both dimensions and perhaps more sophisticated warping and resampling. This will require a good set of image features with which to match, but makes the assumption that the manifestation of seemingly corresponding features in both SAR and fiducial image are in fact in the same physical location. For example, consider a feature that is offset in elevation that might lean one way in the fiducial image, and another way in the SAR image.

Underscoring all this is the presumption that we do in fact have some features that can be corresponded in the fiducial image and SAR image to be aligned. Uniform fields of clutter, such as might be found in many regions with large tracts of crops, or grassland, can be pretty devoid of features suitable for alignment. Figure 2 is an example.

All of these factors, and likely others, will contribute to registration errors between the SAR image and the reference fiducial image. Nevertheless, with a good set of features we should be able to get pretty close. The obvious question is "How close?" to which a natural retort would be "Well, how close do you need?"

So, the answer is an unsatisfying "It depends…"

We opine that a flat horizontal scene with a good set of features and sophisticated warping algorithms might allow us resolution-scale alignment, with the caveat that "resolution" refers to the coarser resolution between reference fiducial image and the SAR image. However, anecdotally, local topography and modest suboptimal registration algorithms will constrain our ability to maximally register the SAR and reference fiducial images. We further opine that meter-scale alignment errors are probably quite tolerable for many applications. Seemingly this should be achievable with substantially fractional-meter resolutions.

Figure 2. Featureless landscape in the Flint Hills region near Wichita, Kansas, USA. Image is about 700 m by 400 m, taken 12 October 2019. Image center location is 37.929936 N, -96.653544 E.

2.3.3 Comments

Mathematically, we might describe our total combined geolocation error as

$$\boldsymbol{\varepsilon}_{total} = \boldsymbol{\varepsilon}_{fiducial} + \boldsymbol{\varepsilon}_{alignment}, \tag{1}$$

where the 3-D error vectors are

$$\begin{aligned} \boldsymbol{\varepsilon}_{fiducial} &= \text{error in fiducial image, and} \\ \boldsymbol{\varepsilon}_{alignment} &= \text{error in aligning SAR image to fiducial image.} \end{aligned} \tag{2}$$

We might argue that additional, as yet undiscussed, errors might also be relevant. For example, we might encounter an error in selecting the representative part of a particular feature that we wish to geolocate in a SAR image. Nevertheless, we judge these to be minor in comparison, and will hereafter ignore these.

Between the two major error categories in Eq. (2), we stipulate that alignment errors can be reasonably expected to be usually held to the meter realm by choosing suitable resolutions for SAR images, and noting the typical resolutions available in Google Earth images. However, the literature suggests that our Google Earth reference fiducial images might be several tens of meters or more in error, although a worldwide average might be more in the several meter range, and some regions might be represented better by a 1-meter limit on location error.

An important point for geolocation is, however, that these errors do 'not' depend on radar operating range, radar navigation accuracy, or even the existence of working GNSS or other navigation aids at the time of data collection.

So, an important question is then "Are the available fiducial images geolocated significantly better than what we can achieve using radar-only methods as outlined in earlier reports?"[1,2,3] Of special interest are any competing Single Image Geolocation (SIG) techniques.

We do note that occasionally maps contain intentional errors to combat plagiarism. These are sometimes called "Map Traps," or more generally "Copyright Traps."[20]

3 Examples

We now provide a pair of examples that estimate the geolocation of specific features in a SAR image based on image registration with fiducial images. The features and images are in Albuquerque, New Mexico, USA.

The publicly released SAR images in the following examples were collected with the Sandia National Laboratories Ku-band MiniSAR system in 2006.[21,22,23] They are range-Doppler images, nominally 10 cm resolution in slant-range and azimuth, having been processed with the Polar Format image formation algorithm. Although the data was collected from a relatively near 3.4 km, the metadata location for the Scene Reference Point (SRP), the nominal center of the image, was significantly in error by about 22 m. The obvious intent is to improve this with the fiducial alignment method outlined in this report.

The fiducial images against which the SAR images were aligned are the Google Earth images from 25 February 2018.[4] While later Google Earth images exist, since the SAR images are from 2006, several useful tie points were no longer evident after 2018, so the earlier reference images were used. Alignment was done manually, based on tie points that did not include the specific features of interest for which we wish to find precise geolocations. That is, although the features we wish to geolocate are visible in the Google Earth images, they were not used in the alignment process, therefore for all intents and purposes invisible in the fiducial images. This is a case of "ignoring data is like not having the data."

We will assume that the actual "truth" locations are measurements provided by a Trimble Geo 7X high-accuracy GNSS handheld receiver (Model #88161). This receiver is specified to exhibit centimeter level accuracy.[24]

<u>Geoid Height</u>

In comparing elevation data, we must be cognizant of the geoid height, which is the local height of the reference surface with respect to (i.e., above) 0 m MSL. For us the reference surface is an ellipsoid model used for the WGS-84 datum. The elevation above the reference ellipsoid is termed Height Above Ellipsoid (HAE). We are conveniently (for us) ignoring just exactly 'which' WGS-84 model we are using.[25]

The geoid height also depends on exactly which model is being used for the earth's gravity, and will fluctuate across models by perhaps even a couple of meters or so in the Albuquerque area.

In the vicinity of southeastern Albuquerque, New Mexico, USA, using the EGM2008 gravity model,[26,27] the geoid height is calculated to be about -20.2 m, with some local variations. This indicates that 0 m HAE is about 20.2 m "below" 0 m MSL. So, a measurement corresponding to MSL will need to 'subtract' about 20.2 m to yield a measurement corresponding to HAE. Other gravity models might offer geoid heights that vary from this by as much as 2.5 m or so.

Google Earth gives elevation in MSL. It is not clear exactly how Google Earth arrived at their numbers, i.e., precisely what geoid database they employ.

3.1 Eubank Gate

SAR feature geolocation via Google Earth fiducial imagery was performed on a utility box cover near the Eubank Gate of Kirtland AFB, pictured in Figure 3, in January 2022. A plan view of the area is pictured in Figure 4, from 25 February 2018, with alignment tie points indicated with red annular ring markers. A Ku-band MiniSAR image from 2006 is aligned to the Google Earth plan view in Figure 5. The feature to be geolocate is designated by the red box. Table 1 indicates the resulting geolocation coordinates and their errors.

Table 1. Coordinates and errors from SAR feature geolocation using Google Earth fiducial image.

	Truth	***Google Earth***	***Aligned SAR***
Latitude (deg)	35.053897148	35.053897	35.053901
Longitude (deg)	-106.533051919	-106.533054	-106.533060
Elevation (m HAE)	1644.96	1646.83	1646.83
Horizontal error (m)	0	0.19	0.85
Vertical error (m)	0	1.87	1.87

The local geoid height was presumed to be about -21.17 m.

Figure 3. Street level view of utility box cover near Eubank Gate of Kirtland AFB.

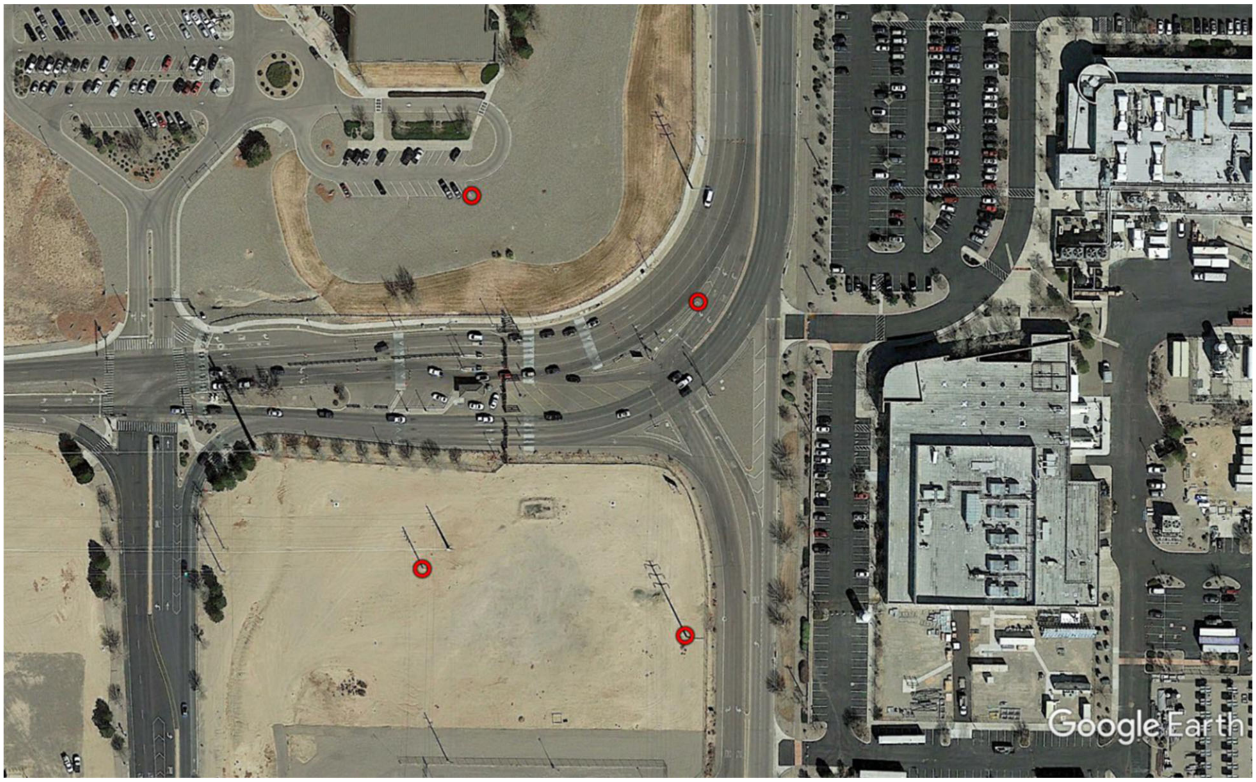

Figure 4. Plan view of Eubank Gate area, with tie points indicated by red annular ring markers.

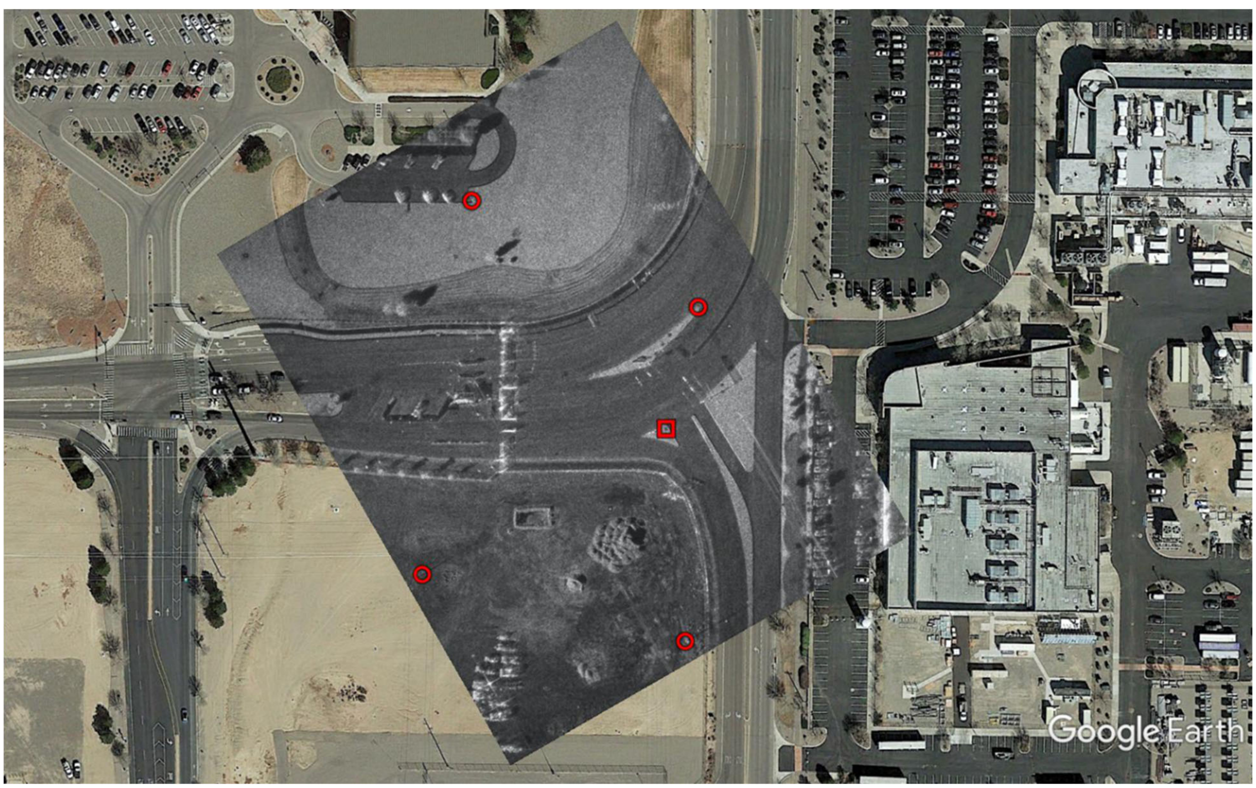

Figure 5. SAR image manually aligned to tie points. Feature to geolocate is utility box cover marked by red box.

3.2 Wyoming Gate

SAR feature geolocation via Google Earth fiducial imagery was performed on a fire hydrant (specifically its base) near the Wyoming Gate of Kirtland AFB, pictured in Figure 6, in January 2022. A plan view of the area is pictured in Figure 7, from 25 February 2018, with alignment tie points indicated with red annular ring markers. A Ku-band MiniSAR image from 2006 is aligned to the Google Earth plan view in Figure 8. The feature to be geolocate is designated by the red box. Table 2 indicates the resulting geolocation coordinates and their errors.

Table 2. Coordinates and errors from SAR feature geolocation using Google Earth fiducial image.

	Truth	***Google Earth***	***Aligned SAR***
Latitude (deg)	35.066373059	35.066371	35.066365
Longitude (deg)	-106.550663001	-106.550663	-106.550659
Elevation (m HAE)	1625.29	1626.69	1626.69
Horizontal error (m)	0	0.23	0.97
Vertical error (m)	0	1.40	1.40

The local geoid height was presumed to be -21.31 m.

Figure 6. Fire hydrant near Wyoming Gate of Kirtland AFB.

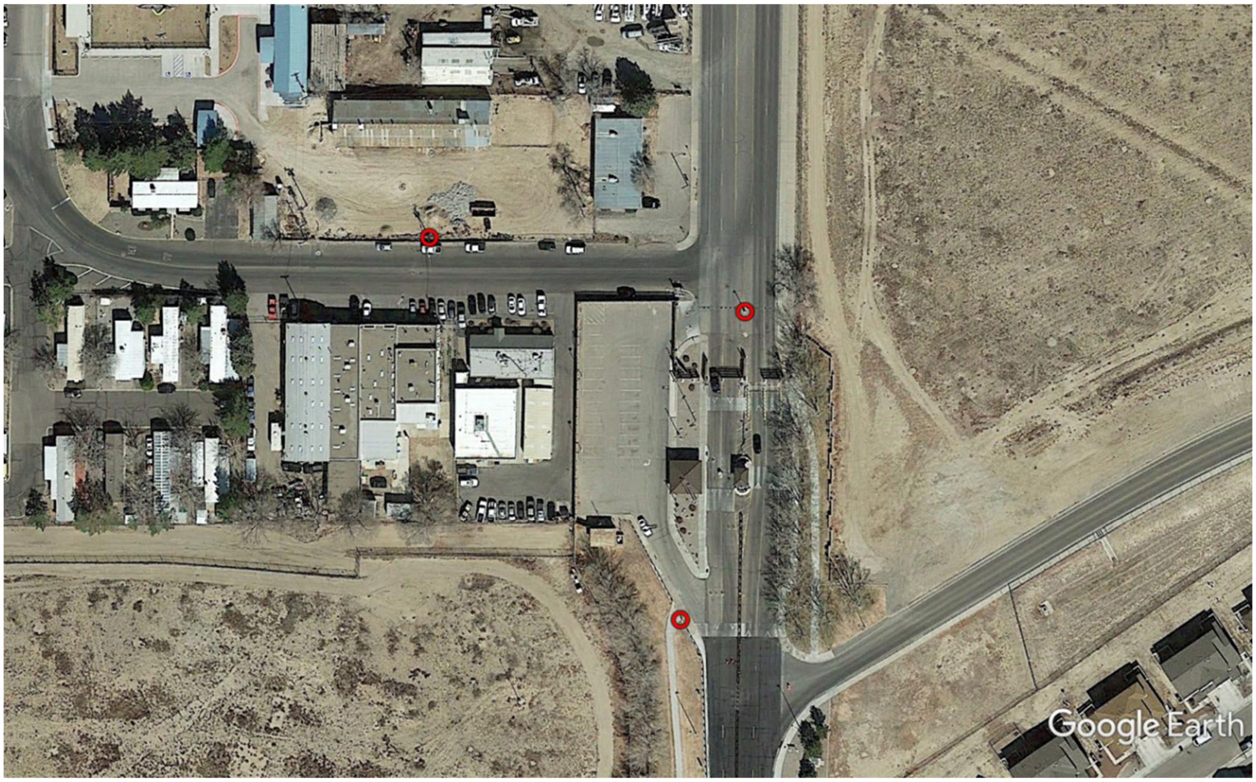

Figure 7. Plan view of Wyoming Gate area, with tie points indicated by red annular ring markers.

Figure 8. SAR image manually aligned to tie points. Feature to geolocate is fire hydrant marked by red box.

3.3 Comments

We make the following observations regarding the examples just offered.

- In both cases, the SAR images' metadata provided horizontal position errors of about 22 m, but aligning the SAR images with local Google Earth images allowed geolocating respective features of interest to within about 1 m horizontally, and less than 2 m vertically. This is a great improvement. Of course, that's the idea.
- In both cases, SAR and Google Earth images contained suitable features to use as tie points for image alignment, which was performed manually.
- Observable features do change over time. Consequently, it is important to consider the difference in creation dates of the SAR image and reference fiducial image. For the examples given, we needed to go back in time and recall archived Google Earth imagery.
- We need to be mindful of the difference between MSL and HAE for elevation data. The difference is the geoid height (HAE - MSL). This can be tens of meters, and specifically in the Albuquerque area where the examples are located, is about -20.2 m using the EGM2008 gravity model, but does still vary somewhat.
- Some more about geoid calculations. Local geoids are calculated by interpolating between what amounts to gravity sample locations. So, not only are there differences between various gravity models, but the specific geoid value for a given location will depend on just exactly how the data are interpolated. Different tools and resources will do this differently. We note that the EGM2008 gravity model used herein has a surface resolution of about 5 minutes of arc by 5 minutes of arc.[26] With the nominal earth's radius being 6371 km, a 5 minute arc corresponds to about 9.2 km.

  Nevertheless, we may reasonably expect that any errors due to the geoid model used, or interpolated calculations, are probably not significantly greater than the expected underlying errors in Google Earth elevation, especially since Google Earth's elevation precision seems to be 1 m.

4 Summary and Conclusions

We offer and repeat some key points.

- The nature of any radar is to geolocate its echo data, i.e., in our case SAR images, relative to its own measured radar location. But this doesn't have to be the only way.
- Databases of geolocated earth imagery do exist, often using other imaging modalities such as optical, with Google Earth being one such example. These can often be much more accurate than what might be achievable by the radar itself.
- SAR images may be aligned to such a higher accuracy database, thereby improving the geolocation of features in the SAR image. Resulting meter level accuracy has been demonstrated.
- The choice of image features to use as suitable tie-point locations is very important. They must be readily identifiable in both the SAR image as well as the fiducial image. Ideally, tie points would be very localized, perhaps even point-like. However, long linear features may help register in some directions, but not others
- In particular, we need to be cognizant that feature elevations might use different metrics, such as Mean Sea Level instead of Height Above Ellipsoid. The difference between this is called the geoid, for which earth maps exist.
- SAR image registration to fiducial images or maps has been proposed as an aiding scheme for aircraft navigation. In this case, the registration corrections are essentially related to position offsets of the radar-carrying aircraft.[28]

"Missed it by that much."
-- Maxwell Smart, Get Smart television series, NBC/CBS, late 1960's.

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“Believing oneself to be perfect is often the sign of a delusional mind.”
-- Data, to Borg Queen, Star Trek: First Contact

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