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SAR Image Registration in Absolute Coordinates Using GPS Carrier Phase Position and Velocity Information

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BIOGRAPHIES

Mr. Scott Burgett is a Member of the Technical Staff in the Aided Navigation and Remote Sensing Systems Department at Sandia National Laboratories. He holds a BSEE from Kansas State University and a MSEE from the University of New Mexico. Scott is active in synthetic aperture radar applications, interferometric SAR applications, and very high accuracy aided navigation systems.

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ABSTRACT

It is useful in a variety of military and commercial applications to accurately register the position of synthetic aperture radar (SAR) imagery in absolute coordinates. The two basic SAR measurements, range and doppler, can be used to solve for the position of the SAR image. Imprecise knowledge of the SAR collection platform's position and velocity vectors introduce errors in the range and doppler measurements and can cause the apparent location of the SAR image on the ground to be in error by tens of meters. Recent advances in carrier phase GPS techniques can provide an accurate description of the collection vehicle's trajectory during the image formation process. In this paper, highly accurate carrier phase GPS trajectory information is used in conjunction with SAR imagery to demonstrate a technique for accurate registration of SAR images in WGS-84 coordinates. Flight test data will be presented that demonstrates SAR image registration errors of less than 4 meters.

INTRODUCTION

Synthetic aperture radar images display the intensity of radar return of an area of illumination by filtering returns according to range and range rate (or doppler frequency, equivalently). For a target that appears in a SAR image, there are two fundamental measurements available to help determine the target location, range and range rate. Using these two observables, it is possible to use one SAR image and solve for latitude and longitude (target height must be estimated or known a priori).

The SAR image registration/precision targeting problem has received attention in the precision strike community recently [1], [2], [3]. The approach taken in this paper is to solve the range and range rate equations directly to register the image in latitude and longitude. Height is either known a priori or estimated. In a recent flight test, SAR imagery of a scene with known coordinates was collected, and both the real time and kinematic GPS position and velocity information were recorded. The degree of improvement in image registration using this data is discussed.

KINEMATIC PROCESSING

The GPS carrier phase system consists of two NovAtel GPSCard™ 10 channel C/A code receivers. One of the receivers, equipped with an antenna choke ring, was used as the monitor station at a known location. The second NovAtel receiver was flown on Sandia's Twin Otter aircraft.

Both receivers recorded GPS data at one hertz. Five to eight satellites, visible above a ten degree mask angle, were common to both receivers for the entire data collection. The flight was preceded by a forty minute static period and followed by a twenty minute static period at approximately the same spot as the starting location.

The carrier phase data was post-processed using SEMIKIN™, which uses a double difference carrier phase model for static and kinematic positioning [4]. The initial forty minute static period was used to initialize the carrier phase ambiguities. Theoretically, since five or more satellites were present during the entire mission, all cycle slips should be detected and corrected.

Four methods were used to determine the reliability of the carrier phase solution. The first method was to compare the estimated final kinematic position of the Twin Otter with the static solution obtained by using the final 20 minutes of stationary data. The horizontal difference was 34cm and the height differed by 30cm. This is higher than would be expected if the ambiguities were resolved correctly and all cycle slips were detected and corrected.

The second method used was to process the carrier phase data in reverse time and compare it with the forward solution. The 20 minutes of static data at the end of the flight was used to resolve the ambiguities, then the data was processed in reverse time. The reverse solution differed with the forward solution by an average of 22cm in latitude, 16cm in longitude and 30cm in height. Since the forward and reverse solutions should be identical, these results indicate either incorrect resolution of the ambiguities or cycle slip detection/correction troubles.

The third method is to look at the residuals of the satellite pairs. The residuals remained within a +/- 8cm boundary. There appeared to be a common epoch in time when a few of the forward and reverse processed residuals had a sudden shift. Further inspection of the SEMIKIN output files that contain the cycle slips indicated all satellites the monitor receiver was tracking had cycle slips at this time. From this moment forward (or reverse) the ambiguities are probably incorrect. The most reliable solution is to use the forward solution up until this epoch, and the reverse solution from that time on. It is worth noting that the period of interest in this investigation, 315300 to 316000 seconds, lies in the reverse portion of the combined data, and there was only one detected and corrected satellite slip (due to a new satellite rising) between this period and the final 20 minute static period.

The final method compared the combined (forward and reverse) carrier phase kinematic solution with a differential carrier smoothed psuedorange solution. The carrier phase solution compared to within 1 meter horizontally and 3 meters vertically of the carrier smoothed differential solution. These results are what would be expected, and the comparison was made to assure the carrier phase solution is reasonable.

EXPLANATION OF FLIGHT EXPERIMENT

The SAR data used in this investigation was collected by the Sandia National Laboratories (SNL) Twin Otter Radar Testbed. It produces 1 meter resolution SAR imagery. Navigation and motion compensation are accomplished in real time using a Texas Instruments 6 channel P-Code GPS receiver integrated open-loop with a 1 nautical mile per hour Honeywell IMU mounted on the SAR antenna gimbal.

For this experiment, a radar tophat was placed on a reference point near the Sandia Labs Rocket Sled test facility. The Twin Otter then flew a circle around this reference point, imaging the tophat every five degrees of aspect change. In all, 66 images from this flight were used in the experiment.

All the SAR images were stored on disk in data files. Each file has a header which contains the relevant information needed to solve for target horizontal coordinates. This information includes the position and velocities of the SAR antenna phase center at the center of the synthetic aperture, as well as GPS time, the SAR range to beam center, depression, squint, and image orientation with respect to north.

Each image was displayed on a Sun workstation, and the pixel location of the reference point (marked by the tophat) was determined and stored with the other image parameters.

SOLUTION PROCEDURE

As stated earlier, the basic information available in SAR images is range and range rate. The range measurement is quite accurate, but the range rate measurement is actually an integrated measurement. There is no instantaneous range rate measurement available from the SAR image. Ideally, one would like to have the instantaneous range and range rate at the center of the synthetic aperture to use in solving for the latitude and longitude of the image.

Figure 1 is an illustration of the SAR image frame for the SNL SAR. Note that these images are formed so each row is constant range, and each column is constant azimuth. The following is a key of the relevant quantities used for SAR image registration:

- ϕ - depression angle
- θ - squint angle in the slant plane
- SCLA - scene center line angle wrt North
- r_b - slant range to beam center
- δr - range from scene center to scene reference point (SRP)
- δa - azimuth from scene center to scene reference point
- APC - antenna phase center
- **D** - the unit vector between the APC and the SRP
- V_x - APC velocity in the X dimension

In broadside SAR, the image is formed according to a desired V_x, squint angle, and depression angle. Over an aperture, the antenna phase center does not traverse a straight line in the x direction. SAR motion compensation must determine any position and velocity perturbations off nominal in order for the SAR processor to correctly form the image.

Ideally, the APC velocity along the boresight, line of sight velocity, V_{los}, is zero. It typically is not and the motion compensation system supplies V_{los} to the SAR processor so a correct range rate may be computed. Imprecise knowledge of V_{los} will skew the doppler spectrum, in essence causing the apparent location of the image patch to be shifted in azimuth. The equations for range, range rate, and azimuth shift are summarized below:

$$\text{Range} = r_b + \delta r \quad [1]$$

$$\text{Range Rate} = V_x \bullet \mathbf{D} \quad [2]$$

$$\text{Azimuth Error} = \frac{V_{los\ error} r_b}{V_x} \quad [3]$$

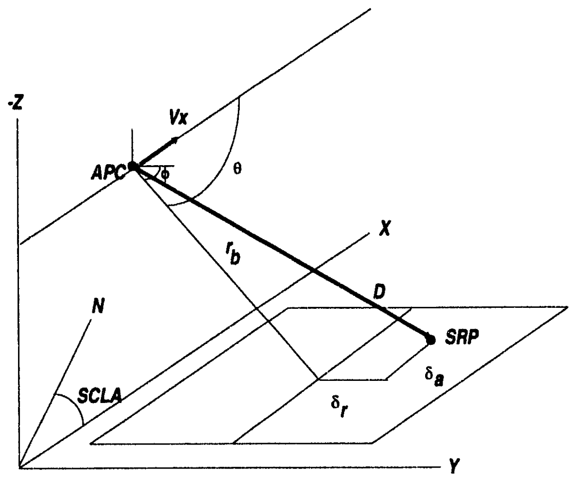

Figure 1. SAR Image Parameters

Each SAR is slightly different, but in all SARs a pixel's range and range rate is encoded in its location in the image. In this investigation, the range and range rate of a known reference point in the image, marked by a tophat, was determined. Then, the latitude and longitude of the reference point was determined by solving the range and range rate equations coordinatized in WGS-84 coordinates. A closed form solution could not be obtained, so a numerical solution was computed using a steepest descent technique. Reference 1 contains a thorough derivation of the solution technique.

Image Registration Using Real Time Data

As a baseline performance metric, the horizontal image registration error was computed using the position and velocity information available from the real time navigation and motion compensation system, stored in the image header information. The accuracy of the position and velocity information is typical of P-Code GPS performance. Figure 2 shows the radial (horizontal) image registration error. The CEP (median value) is 5.7 meters. Except for a period of poor performance around time 3.158e5 seconds, the error is bounded by 10 meters. This performance is typical given the navigation accuracy of the GPS/INS combination.

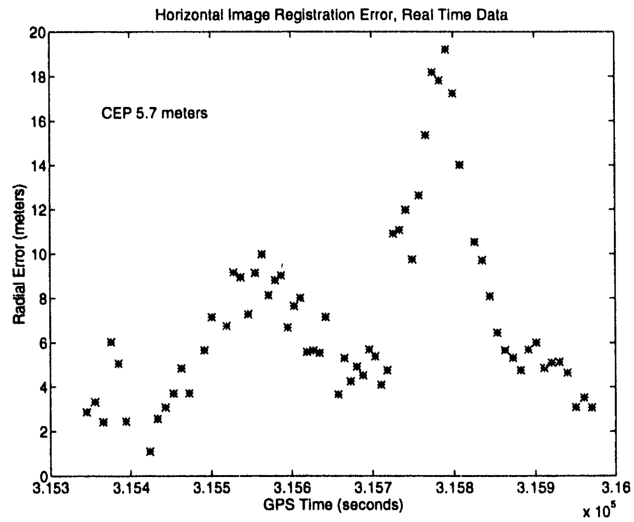

Figure 2. Radial Registration Error, Real Time Data

Image Registration Using Kinematic Position and Real Time Velocities

As described earlier, carrier phase GPS information was recorded on the ground at a reference location and on the Twin Otter. This data was processed using SEMIKIN. The position of the SAR antenna phase center (APC) at the center of the aperture was computed from the kinematic solution using linear interpolation. This updated position information was then used to register the SAR images.

Figure 3 is a plot of the registration errors obtained using this technique. The CEP has been reduced to 3.8 meters. Not that there is still a period of poor performance at time 3.158e5 seconds. While the CEP improved, there are still some troubling aspects to this result. Figure 4 is a plot of the improvement in the position solution due to using the kinematic solution, and the improvement in image registration. In theory, this plot should track each other closely. In fact, they do some of the time. But at other times, they do not track well. Most troubling, using the carrier phase derived positions actually degraded the solution at times.

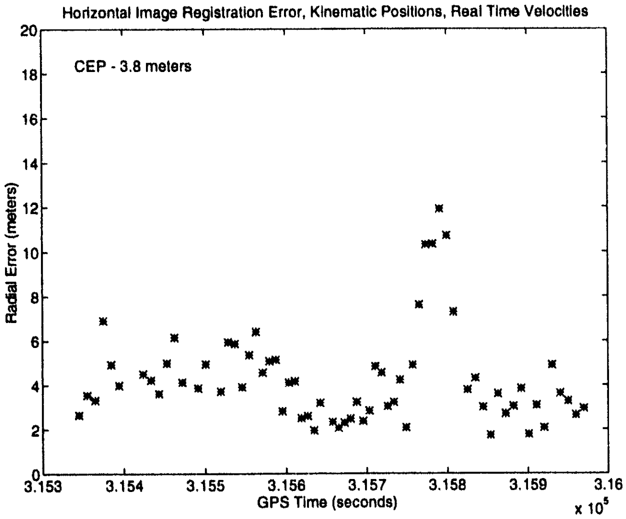

Figure 3. Radial Registration Error, Kinematic Position and Real Time Velocity

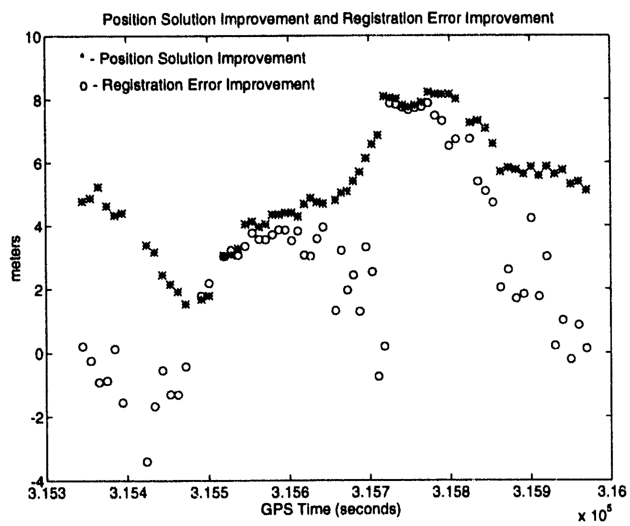

Figure 4. Position Solution Improvement and Registration Error Improvement

An explanation of this is not easy to come by in an analytical fashion. Like most SARs, the SNL SAR used in this experiment has limits on deviations from expected values on aircraft position, velocity, and squint and depression angles. Most likely, in the regions where performance is degraded, one or several of these quantities went out of bounds, causing unknown effects. Other causes for the poor performance are being investigated.

Image Registration Using Kinematic Position and Velocities

In this experiment, the kinematic velocities were used to compute the range rate to the reference point, rather than the real time velocities. Ideally, one would like to compare the computed V_{los} with the V_{los} used by the radar to form the image, and apply this correction to the range rate as well. Unfortunately, the SNL SAR does not record enough information in the image header information to allow the computation of the line of sight velocity used to form the image. Thus, the registration improvements using the velocities are not as good as they could be.

The range rate computed from the kinematic velocities did not vary significantly from the real time range rate. The primary sensitivity in position errors is in range rate. The kinematic velocities are used in the numerical solution, but it appears that the numerical solution is not very sensitive to small changes in velocities if the range rate does not change significantly. On the other hand, V_{los} may have changed significantly due to the more accurate velocity information, but this correction could not be applied.

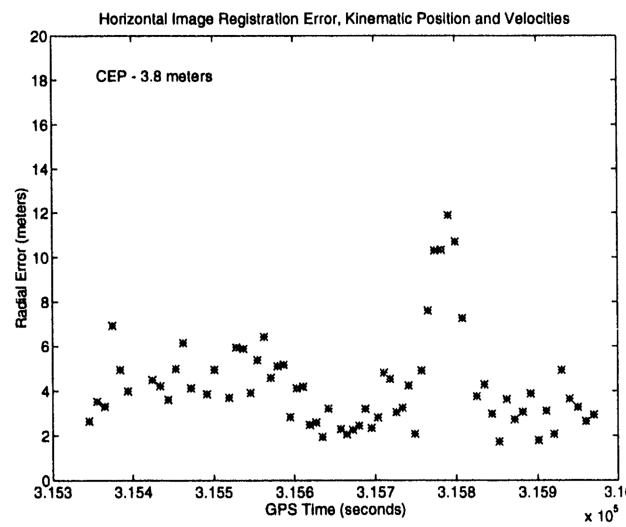

Figure 5. Image Registration Errors Using Kinematic Position and Velocity Information

Figure 5 is a plot of the image registration errors using kinematic positions and velocities. It is essentially the same as Figure 3. This is expected, however, if one inspects Figure 6. In Figure 6, the positional perturbation caused by the difference between the kinematic range rate and the real time range rate is plotted along with the difference between the full kinematic registration errors and the kinematic position and real time registration errors. It appears that the perturbation caused by the small range rate corrections are not enough to displace the solution significantly.

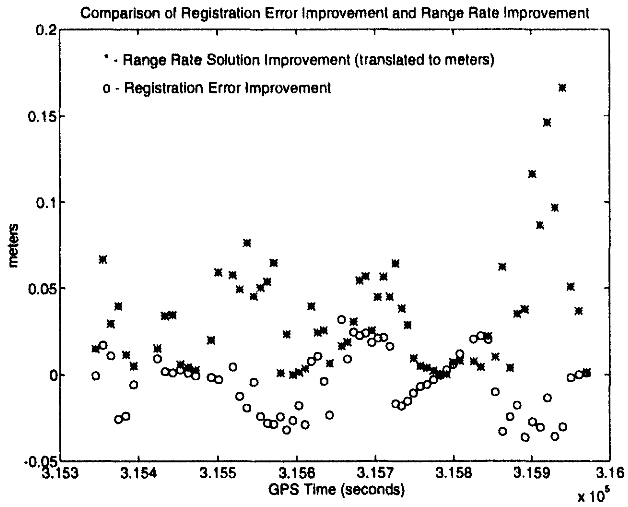

Figure 6. Registration Improvement and Equivalent Range Rate Improvement

ANTENNA ATTITUDE DETERMINATION USING KINEMATIC METHODS

There has been recent interest in estimating the attitude of the SAR antenna very accurately using kinematic methods. If the attitude of the antenna is known very accurately, one can register the SAR image in y and z using this pointing angles only. The x dimension (azimuth) will still be only as accurate as the range rate measurement. This is a very promising new technique, since it allows a SAR image to be registered in all three dimensions very accurately.

SUMMARY

SAR image registration requires very precise knowledge of the collection platform position and velocity during the aperture. Using kinematic GPS techniques to compute platform position and velocities, image registration accuracy can be improved. For greatest registration accuracy improvement, the velocities should be used to compute an updated range rate and line of sight velocity. V_{los} was not available in the data set analyzed in this paper. However, if V_{los} is available, any discrepancy between the V_{los} used to form the image and the actual V_{los} can be corrected, increasing accuracy further.

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