

Co-location of aircraft and radar data.

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(with much help from Al Rodi)

The focus of this short report is an assessment of the precision with which King Air aircraft and SPol radar data can be co-located in space. The question is more general, of course, but no attempt is made here at a comprehensive study. The report is just a summary of my foray into this territory. The goal in reporting the findings here is to let others know my conclusions and to, hopefully, learn from others of better or simpler solutions.

The problem is obvious: Since aircraft and radar data are generated in different position reference systems, some conversion is needed to a common system that allows ready determination of aircraft position (and the in situ and remote sensing data from that platform) with respect to the array of radar pixels. One good choice for this is to use the East-West, x , and North-South, y , distances to a target point (radar pixel) or aircraft position.

Aircraft position from the GPS is given as latitude and longitude, $[lat,lon]_{ac}$. These data are smoothed with IRS data when there are interruptions or glitches in the GPS signal, but in most cases the the GPS data is the defining input.

The native coordinates for radar data are *range* (R), *azimuth* (A) and *elevation* (E). which convert by simple trigonometry to $[x,y,E]$. These are referenced to the location of the radar, $[lat,lon]_{SPol}$, in this case SPol on Barbuda. Without tracking back to details, I assume that the position and the azimuthal orientation of the radar are known with adequate precision.

The conversion of range, azimuth and elevation to $[x,y,E]$ is trivial if diffraction of the beam is neglected. These values are, in reality, with respect to a tangent plane to the Earth at the location of the radar. The difference between distances in this tangent plane and along the surface of the Earth are also readily calculated; for distances of the order of 100 km from the radar, the difference is of the order of 10 m. This is left as a

second-order correction, easily done, and is not part of the treatment here.

Three basically different approaches to the coordinate conversion problem exist: (i) geometry (cartography, geodesy, ...), (ii) radar ‘hits’ i.e. anomalously high reflectivity values in some radar pixels due to the aircraft being in that location, and (iii) alignment of time traces of in situ data with segments of radar reflectivity data. The difficulty with (i) is that one has to deal with the complexities of the shape of the Earth. Radar hits are, in principle, excellent indicators of co-location but the quality degrades with distance from the radar due to the increasing size of the radar bins, and in all cases several bins may record high values. The third approach is the most subjective, and is limited by probe and radar sensitivities by the lack of complete simultaneity.

(i) Geometry

Here I want to look only at the coordinate transformation $[lat,lon] \rightarrow [x,y]$, regardless whether that refers to the aircraft or a radar pixel.

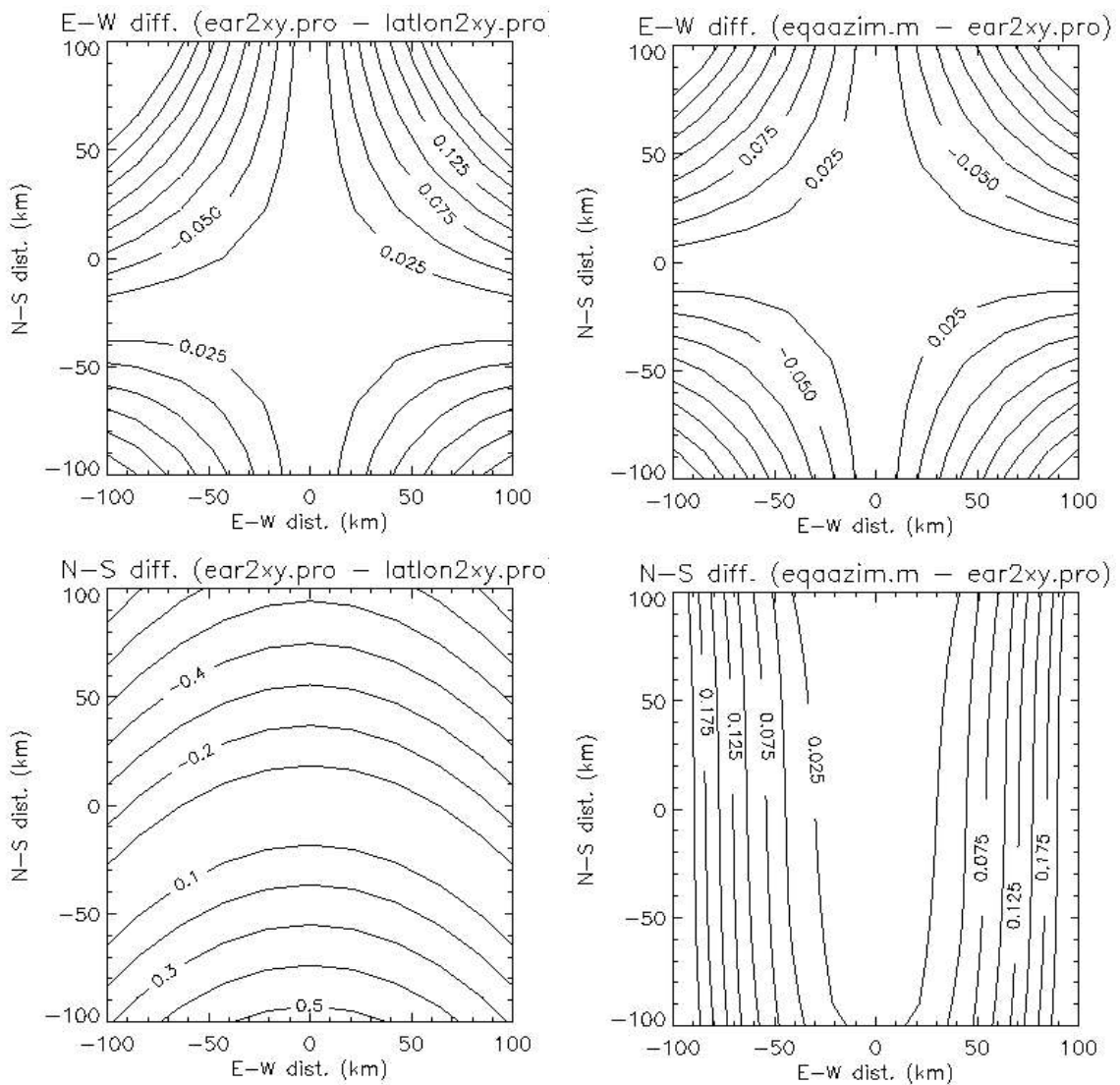
One set of conversions is built into the **solo-ii** radar analysis software. The basis for this code is the ECEF/ENU point transformation¹. The ECEF frame has its origin at the earth's center and the basis vectors point to along the axis of rotation and two perpendiculars to that. The ENU frame is centered at some point on or above the earth's surface and point true east, north and up. The conversion in the solo-ii algorithm uses the oblate elliptical rotational shape of the earth and, if I am not mistaken in reading the code, carries out the transformation assuming a spherical surface with radius computed from the oblate ellipsoid at the locations of the radar unit and of the target point. The IDL version of the solo-ii routine I use below is **latlon2xy.pro**.

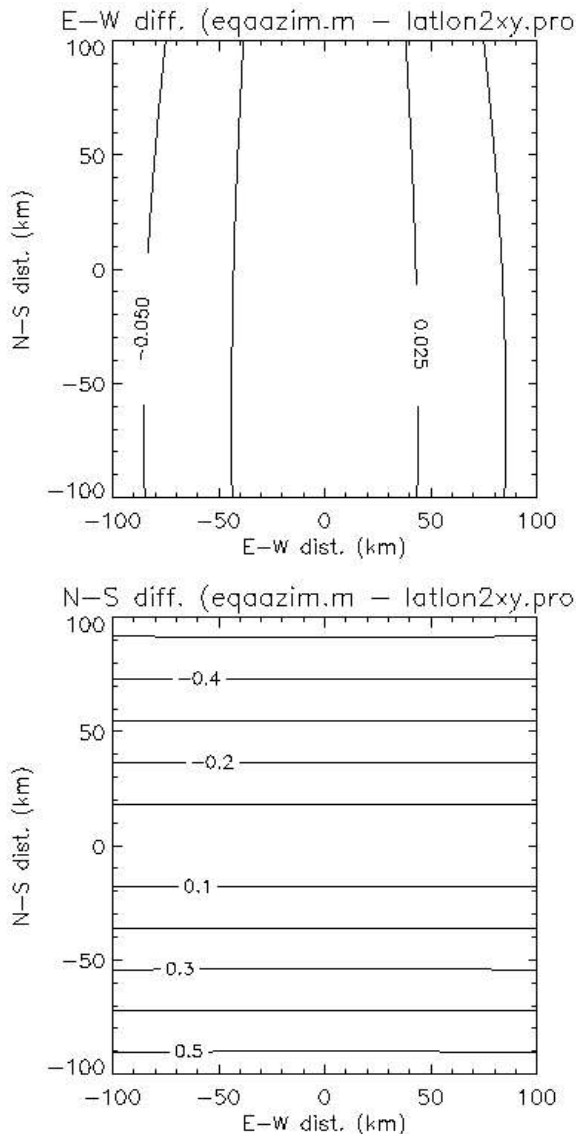
Another tool is the MATLAB routine **aqazim.m** routine. This routine generates radial distance and azimuth for two points whose latitudes and longitudes are given. The detail of the routine is not known; it appears that a great-circle distance d and direction θ with respect to north are calculated from the latitude/longitude values for a pair of points. These are converted to $[x,y]$ with simple sine and cosine operations.

¹ “Aerospace Coordinate Systems and Transformations” by G. Minkler and J. Minkler, Magellan Book Co., Baltimore, MD. 1990.

I wrote a third algorithm in IDL, **ear2xy.pro**. The basis of this routine is a calculation of the curvature of the Earth along latitude and longitude lines. The east-west curvature is that of a circle whose radius is calculated from the equation of an ellipse with major and minor radii of the Earth. The north-south curvature is derived for an ellipse (Hutte 28, 1955, pg. 139). This method doesn't handle properly the convergence of latitude circles even though the mean position is used between the radar site and the target point.

The **[x,y]** values calculated with one or another of these methods can differ significantly. Differences between the results from the three algorithms are shown below and on the next page; contour values are given in km.





For simplicity these comparisons are for points on the surface ($alt=0$). The input to the calculations was an array of lat/lon values for the target point, centered on the SPol location. As the figures show, none of the three algorithms agree and there are differences of up to 0.5 km. The largest differences are with respect to the latlon2xy routine which mimics the solo-ii calculations.

The conclusion from this exercise is that the errors in the $[lat,lon]$ to $[x,y]$ coordinate conversion routines, due to different approximations in the algorithms, are not significant and may exceed other error sources. Thus, there is room for improvement here. The outlier seems to be the solo-ii (latlon2xy.pro) algorithm.

(ii) Radar 'hits' on aircraft.

To see how effective such event might be in determining relative positions of the aircraft in the radar scan, I used two examples from 20041213. Finding the events was relatively easy: reflectivity values in a few pixels about 20 dBZ over the rest of the small cloud constituted pretty good evidence, and that could be further confirmed by the proximity of the aircraft from its track data. During one pass, two pixels had excessive reflectivities, in the second one four. The table below shows the data, and the positions calculated via the three algorithms discussed earlier. The events were at about 70 km from the radar site so they provide a difficult test case for the position comparison but are

limited at the same time by the radar volume resolution. At closer range the resolution would be better, but I suspect that more radar pixels will have excessive reflectivities and provide the same sort of ambiguities in the end.

Comparison of position data for King Air 'hits' during 20041213 flight

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		measured	calculated (km)		
			solo-ii/latlon2xy	eqaazim	ear2xy
		KA GPS (note 1)			
20:37:51 UTC	lat	18.1442			
	lon	-61.9730			
	xpos		-15.73	-15.73	-15.76
	ypos		59.74	59.41	59.42
	SPol via solo-ii (note 2)				
	lat		18.1395		
lon		-61.9716			
xpos ± 0.84 (note 4)		-15.62		-15.64	-15.67
ypos ± 0.29		59.25		58.94	58.95
		KA GPS (note 1)			
20:39:46 UTC	lat	18.1454			
	lon	-61.9754			
	xpos		-15.98	-15.99	-16.02
	ypos		59.87	59.54	59.54
	SPol via solo-ii (note2)				
	lat		18.1409		
lon		-61.9746			
xpos ± 0.86		-15.94		-15.85	-15.88
ypos ± 0.36		59.38		59.16	59.17

note 1: King Air GPS data taken from 1-Hz file, reading a single value without smoothing

note 2: for hit at 20:37:51, using data from one of the two (the Eastern one) pixels with equal reflectivity (36 dBZ)

for hit at 20:39:46, using center of four adjacent pixels (33, 37, 41, 46 dBZ)

note 3: using the difference between the GPS and SPol values via 'ear2xy'

note 4: radar pixel size is 0.8° in azimuth and 0.15 km in range

The table indicates as 'measured' values the GPS position of the aircraft and the [x,y] position of the target pixel. The $[lat,lon]_{tp}$ values (referring to the target point) read from solo-ii are based, I assume, on conversion from $[R,A,E]$ to $[x,y]_{tp}$ (here assumed to be error free due to its simplicity) and then to $[lat,lon]_{tp}$ via the reverse of the solo-ii

algorithm discussed earlier.

The results indicate that there is better agreement between $[x,y]_{tp}$ values extracted from solo-ii and those computed for the aircraft position with either the eqaazim.m or ear2xy.pro routines. These are the values in the highlighted boxes in the table. The agreement here is within 100-150 m, which is still not excellent for detailed comparisons of aircraft and radar data but will be hard to improve on. The solo-ii (i.e. latlon2xy.pro) conversion shows larger discrepancies. This is consistent with the findings from the algorithm comparisons of Section (i).

(iii) Matching data segments.

Working with isolated clouds allows for matching a time series of aircraft data with a selected 'section' of radar data. There are obvious limitations to this approach, due differences in measured parameters (Z versus LWC and size distributions) and in timing of the samples. So, this is mentioned here only for completeness and as the likely method that will actually be employed in most studies.