

Improved correction methods for measuring altitude by Radar and Barometer

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***Abstract:** Geometric altitude of air targets may be found from radar or barometric measurement. However, radar rays are affected by changes in refractive index gradients which result in non-normal bending of rays. Similarly, precision of barometric altitude is affected by the atmospheric deviation away from barometer standard calibrated sea level temperature and pressure, and deviation away from standard temperature lapse rate. Together these effects may lead to hundreds of meters of difference in match between barometric geometric height and radar geometric height. In this report we are proposing two alternative altitude correction methods. Both methods are applied to pairs of ground radar and barometry altitude of civilian airplanes. The most promising of the methods relies on using the meteorological atmospheric forecasting model AROME Arctic. For several of our measurement series this procedure reduces averaged difference between barometric altitude and radar altitude from 400-700 meters down to about 100 meters.*

1. Introduction

This paper suggests methods for improved aircraft geometric altitude calculations. We consider altitudes estimated from ground based radar and from barometric measurement.

Air vessels are localized in three dimensions, of which latitude and longitude relate objects to positions projected onto the earth surface. The third coordinate is usually either Flight Level (FL) barometric pressure above the sea surface, or geometric altitude estimate from radar. FL is measured using atmospheric pressure of the atmosphere right outside the vessel. Most vessels have well calibrated barometers with standard atmosphere as reference in order to avoid mid-air collisions. However, in order to obtain geometric height from FL one needs knowledge of actual temperature in altitudes from sea level to target, as well as offset from the normal 1013,15 mbar pressure at sea surface.

Radar altitude estimate is in principle found from interval between send and receive of an electromagnetic signal reflected from target, as well as elevation angle towards target. However, the capability of any civilian or military Primary Surveillance Radar (PSR) in terms of precisely finding the geometric altitude of a single target is dominated by the model of the state of the atmosphere between radar and target. The main effect of vertical atmospheric refractivity variations on radar height measurement is bending of all radar rays that are not aimed exactly vertical. One often approximates the refractivity slope as changing linearly with height. Since our reference system, earth, already implies curvature relative to the beam, it is usual to calculate an ‘effective’ earth radius to incorporate atmospheric refractivity gradient.

The correction is usually set by modifying the physical earth radius in calculations by a standard factor of 4/3, although this is a known oversimplification of a value which will vary considerably over different areas of the world and with different seasons and times of day.

The most common method for calculating refractive index is by using radiosonds or possibly other air platforms, and measure water vapor pressure, air pressure and temperature of the atmosphere locally. Refractive index is a function of these parameters. However, this is a labor intensive method and in many cases won't produce representative results. Any radar used against air vehicles should be able to locate targets up to 12.000 meters Above Sea Level (ASL) and over large distances, up to 400 km, and a balloon journey will only contribute a single vertical set of measurements. What is really needed is a system which is able to adjust its correction parameters according to changing meteorological conditions without depending too much on manual procedures. In this report we are proposing two alternative methods, both based on radar and barometric altitude measurement of civilian airplanes.

Civilian Secondary Surveillance Radar (SSR) in mode Surveillance (mode S) can interrogate air vehicles about their altitude and position data, which may include Global Navigation System Satellite (GNSS) geometric altitude estimates and meteorological data. Mode S is currently replacing the earlier mode Charlie (mode C), which only gives barometric Flight Level (FL) information. However, in Norway we only have SSR mode C interrogated FL barometric data widely available for alignment with PSR data, and we have found broadcasted navigation ADS-B data hard to associate with the correct set of PSR data. Therefore mode C interrogated FL is used for all our analysis. FL barometric values, using only standard values for atmospheric temperature or humidity variations with height, will usually lead to overestimates or underestimates of geometric height. In particular, in cold weather, the flight computer will overestimate height if one doesn't correct for outside temperature, and thus increasing risk of hitting terrain.

However, the operational aim for air surveillance is really to find a good common reference altitude for barometric and PSR and other sensors over a period of time and distance, and the geometric altitude itself is not usually of importance. The common reference altitude is used to resolve and track air vessels, discover non-responding vehicles or anomalous navigation, and to compare vehicle tracks generated by different sensors. In our investigations we are using FL and PSR from available civilian target vessels of opportunity. These have been collected and paired for different air vessel positions. In the first method radar correction parameters are found directly by a regression process involving measured apparent (uncorrected) PSR and FL altitude over a selected time interval, typically the past 4 hours. The required update rate for the radar correction parameters will depend on the stability of the atmosphere. Our very simple forecast for the next few hour(s) is that the atmosphere remains unchanged. The second prediction method uses the forecast model AROME [3], which is a physical model of the atmosphere and uses a variety of sources as input. The outputs are temperature, lapse rate, humidity, refractivity etc. for multiple horizontal layers.

2. Use of meteorological data in altitude corrections

Barometers for navigation can operate in different modes. The basic barometric data used in this paper is FL, which is assuming standard atmosphere for barometer, and is only emitted by air vehicles at or above a regulated altitude, which is called the Transition Level (TL). In

order to obtain altitude one should correct for sea level pressure correction relative to 1013,15 mbar and temperature and temperature gradient corrections relative to standard values. Our altitude data is thus limited by the TL in Norway, which is never lower than 5500 meters ASL. We also limit our altitude data to a maximum of 11.000 meters ASL, in order to stay within a zone of assumed constant atmospheric temperature lapse rate. Our method for temperature correction is based on ‘EUROCONTROL Guidelines for Cold Temperature Corrections by ATS’ [1]. Temperature does not change considerably with altitude between 11.000 and 20.000 meters ASL and the method isn’t really meant to be applied to air targets above 11.000 meters ASL. Equation (1) illustrates how temperature influences the altitude error. Equation (1) assumes standard atmospheric temperature lapse rate of 6.5 °C pr km and 15 °C at sea level as reference, as well as pressure of 1013,15 mbar at sea surface, same as barometer calibration.

$$FL_{corr} = FL \times \left(\frac{15 - t_r - L_0 H_r}{273 + t_r + 0.5 L_0 H_r} \right) = FL \times \alpha \quad (1)$$

- FL_{corr}:** Temperature correction to be applied to FL
- FL:** Uncorrected barometric altitude measurement
- H_r:** Altitude where temperature is measured (= 0 if sea level temperature is used)
- t_r:** Temperature at altitude H_r ASL (may be sea level temperature)
- L₀:** Standard temperature lapse rate (0,0065 °C pr meter)

In our regression method used in chapter 4 we don’t really care about actual sea surface pressure, temperature or lapse rate, but regard the correction factor α as being constant over the 4 hour period over which the correction parameter is estimated. The same constant is used over the following 4 hour period for forecasting. In contrast, in our meteorological model method in chapter 5 we don’t assume a standard lapse rate, but use the AROME Arctic forecasted data to find the temperature lapse rate and the temperature at the target.

Our PSR frequency is in the band 2-4 GHz, with assumed instantaneous elevation uncertainty of about 500 meters. However, we make the following important simplifications, which may be acceptable since in this paper we are looking for long time, large area average performance: We ignore random Gaussian variations in radar detections due to angels, multipath and reflections.

For the method with AROME data, chapter 5, we still do not correct barometric altitude for offset pressure from standard 1013,5 mbar at sea level. Also, in principle we should have based barometric corrections on AROME Arctic data from positions right under the targets, but instead we have merely averaged temperature and averaged temperature lapse rate near the radar latitude and longitude, and applied these data for the area of observations. Similarly, when working out the average refractivity gradient, the upper refractivity value should in principle have been taken at the latitude and longitude of the target rather than at the radar.

3. Calculation of parameters for correction of radar altitude

Both of the radar correction methods we discuss in chapters 4 and 5 are physically based on [2], which shows how Snell's law of refraction explains the effect of refractivity gradients.

According to for instance [1], [4], and [5] the atmospheric refractive index n at altitudes below 50 km depends on the atmospheric pressure p (hPa), the absolute temperature T (K), and the partial pressure of water vapor e , as expressed by (2)

$$n = 1 + \frac{0.373e}{T^2} + \frac{77.6 \times 10^{-6}p}{T} \quad (2)$$

We use calculus of differentiation and denote the gradient by altitude of n by n' , gradient by altitude of e by e' , gradient by altitude of T by T' , and gradient by altitude of p by p' , which leads to (3).

$$n' = \text{wet part} + \text{dry part} = 0.373 \left(\frac{e'}{T^2} - \frac{2T'e}{T^3} \right) + 77.6 \times 10^{-6} \left(\frac{p'}{T} - \frac{T'p}{T^2} \right) \quad (3)$$

We should consider each of the terms of (3) with respect to expected uniformity and stability in three space dimensions plus time. We expect the terms containing p , T and their gradients, the so called "dry" air terms, to be considerably more stable than the "wet" terms. "Wet" also means packages of fog or clouds which we know will be quickly changing position and their form, very much influenced by winds. This is particularly true at high altitudes.

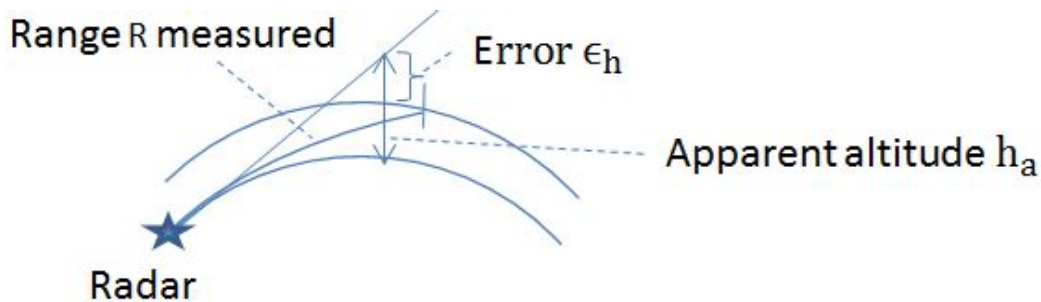


Figure 1. This is an (exaggerated) illustration of error in target altitude due to vertical rate of change of refractive index. R [m] is the radar distance measured, h_a [m] is the apparent radar height measured, and ϵ_h [m] is the altitude error.

We have found [2] to be a particularly useful general reference for discussing corrections of atmospheric refraction errors in radar height finding. It starts off by describing Snell's law of refraction of radio waves in the atmosphere, showing that a gradual reduction of density of the atmosphere with height make upward emitted radio waves bend slightly down towards earth's surface. It should however be noted that there is a "best practice" correction procedure by way of multiplying the earth's radius by a factor 4/3 for all radio wave calculations. Height finding radars employs this correction procedure as a minimum. Sometimes radar systems allow for corrections to be implemented based on input of basic meteorological data, such as the parameters of (2) and (3), if these are available.

4. Regression method for correcting altitude

Paper [2] follows a path of arguments slightly different from the main stream. It takes the reader through a set of simplifying assumptions which end up with (4), and shows that the error in radar height measurement is approximately equal to a geometry factor multiplied by an average refractive index gradient (g) for the path between radar and the object observed, where the gradient g [m^{-1}] is the effective average rate of change of refractive index n of the atmosphere along the path from radar to target. See Fig. 1 for the meaning of the other parameters of (4).

$$\epsilon_h = \frac{(R^2 - h_a^2)^{3/2}}{2R} g \quad (4)$$

The value of g for the specific path between the radar and a target at a particular time may be calculated by (4) if we have a good estimate of the error ϵ_h , the apparent radar height h_a and the radar range R .

In Air Traffic Management (ATM), in order to avoid mid-air collisions, the standard variable for determining relative vertical position between air vehicles is barometric altitude. So, if we can verify the geometric altitude of an air vehicle by reported barometric measurement and estimate ϵ_h we may use equation 4 to calculate the average refractive index gradient. This gradient and equation 4 may then later be used to correct the next radar altitude measurements. However, we must be careful not to use the correction parameters to correct height for a path which is very far away in time or space from the paths used in calculating the correction parameters. In order to proceed we have to solve for the coefficients of a linear equation of two unknowns. Equation (5) models the difference between FL measured altitude and radar measured altitude (left hand side) as difference between FL temperature correction for altitude and radar refractivity gradient correction for altitude, plus model inaccuracy (right hand side). α , g and model inaccuracy are unknowns, and are calculated using multiple linear regression or least squares method on (5) for a time series of PSR and FL data. This method requires stability of the atmosphere over some time in order to collect enough data to cover a representative amount of airspace around the radar. The time needed to collect sufficient data will depend on the density of air vehicles and how often reliable altitude measurement is received on air from each air vehicle and from radar.

$$FL - h_a = FL \cdot \alpha - \frac{(R^2 - h_a^2)^{3/2}}{2R} \cdot g + \text{model inaccuracy} \quad (5)$$

We now assume temperature and temperature lapse rate of (1) to be varying slowly with time, in order to approximate $\left(\frac{15 - t_r - L_0 H_r}{273 + t_r + 0.5 L_0 H_r}\right)$ to a constant α as in (5). The correctness of the model will always be limited by the density of targets and time spent on obtaining the parameter estimates. Equally important is how well air vehicles of opportunity span the airspace of interest around the radar during this time interval. The air vehicles are carrying SSR transponders which supply FL responses to interrogation from ground.

In order to achieve robust regression, one should also consider, as a source of errors, temperature, wind and pressure changes. These may indicate sudden large scale changes to the surrounding atmosphere, which will affect the resulting estimate. The regression estimate should be done in at least two stages on the same input data, with a first stage discriminating extreme outliers in the data to exclude invalid pairs of barometric and radar altitude measurements.

Some results using this regression method were obtained for some days in August 2014, September 2014, and January 2015. The results were quite good for some of the days, and not so good for other days. Some days the absolute value of the average difference between PSR and SSR altitude were reduced by 60-70 %, while at other times the corrections actually led to increase of the difference. The results became better in winter time, probably because colder weather often increases stability.

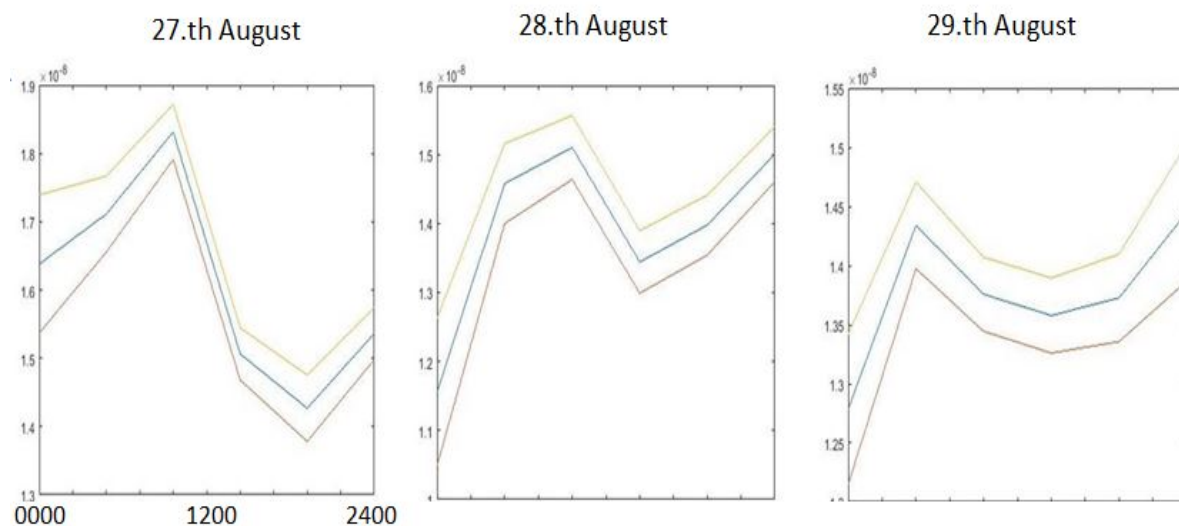


Figure 2 Variation of g [m^{-1}] as function of time of day, with upper and lower bound standard deviation of estimates

We have also investigated the variability of the g factor of (5), see Fig. 2. In this dataset the radar data are already corrected according to the common 4/3 earth-radius factor prior to our corrections. Thus our g corrections reflect an adjustment relative to the common 4/3 factor. We note that relative variations in g value have a standard deviation of typically 5-10 % during a day, and a variation of typically 10-20 % between neighboring 4-hour prediction cycles. We also note that Fig. 2 results repeat as a pattern the following day. However, the repetitions could be explained by the fact that the air traffic is often repeated on a 24 hourly cycle. We sample different locations and altitude of targets during the day, according to the routes of different flights, and this will footprint the result. Fig. 2, which is based on the regression method, indicates about 10 times as much variation in the refractivity gradient compared to the AROME Arctic weather prediction method variation estimate indicated by Table 1 in the next section. Our results using the regression method is very simple and without direct reference to meteorological data, and is a result of an ‘averaged’ refractive

index gradient value over the path from the radar position and altitude to the observed targets' position and altitude, and similarly an 'averaged' sea temperature correction term for the barometric correction.

The high variations in the g value and the fact that the regression results depend on the distribution of target altitudes is a big problem. We have to resort to robust regression methods in order to get rid of outliers. If there are very many outliers this will make the final regression estimate less reliable. This is probably why we haven't found the regression method to be successful over time, and in particular not during warm weather. Paper [4], which investigates the uncertainties of altitude measurements, supports the theory of increased instability in warm weather.

5. AROME Arctic meteorological model method for correcting altitude

Due to the varying success of the regression method we have also investigated a different method, where, with the help of the meteorological forecast model AROME Arctic we have calculated α and g terms of (5) separately. The AROME, which is described in [3], makes use of data from various sources, such as radio sounders, wind profilers, aircraft reports, ship and buoy reports, automated land surface stations, satellite instruments and delay observations from GPS. We have used AROME Arctic 6 hour predictions, even though, according to the Norwegian Meteorological office, the data from the starting 3 hours of every forecast may contain more uncertainty than those from the last 3 hours. The resolution of the model is 2.5 km by 2.5 km in the horizontal plane, and 65 altitude levels ranging from approximately 500 to 29000 meters ASL.

In order to correct our radar data, we replace the standard atmospheric 4/3 earth radius correction by $(\frac{(R^2 - h_a^2)^{3/2}}{2R} \cdot g)$, where the refractivity gradient g is calculated directly from AROME Arctic vertical levels of refractivity between radar and target.

Having obtained this more accurate radar target height, we now use the AROME Arctic meteorological data in order to find the temperatures at that target height, and thus also the temperature at sea level, using the AROME Arctic predicted temperature lapse rate.

According to [6] one expression for the correction factor α of (5) is $\frac{T_{m_{isa}} - T_m}{T_m}$, where $T_{m_{isa}}$ is the mean temperature between actual temperature at target and standard temperature at sea level (288,15 °C), and T_m is the mean temperature between actual temperature at target and actual temperature at sea level. We don't apply a local temporary sea level pressure correction. Our FL data are restricted to altitudes greater than 5500 meters in order to ensure that no local corrections to barometer settings should be present, and less than 11.000 meters to ensure that we are in the constant temperature lapse rate zone.

We use AROME Arctic data from 13 days in January 2017 and 2 days in March 2017, but we only have radar observations for 9 days in January and the 2 days in March. The results are

visualized in Fig. 3. The ‘*’ points are for the original standard atmospheric differences, and the ‘o’ show data after AROME Arctic based corrections are applied. After correction is applied we see improvement in the difference between barometric and PSR altitude of several 100 meters compared to the uncorrected difference, and in many cases down to a difference of around 100 meters. On most days we see at least some improved performance compared to the original FL minus PSR value. However, on days 1, 2, 13 and 14 the performance of the AROME Arctic method is about the same as of the uncorrected FL and data. On day 9 the met data in Table 1 predict a clear worsening as the deviations of temperature gradient values are big compared to other days, which indicates that the model maybe shouldn’t be used on this day.

Day no	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
% Refractivity															
gradient deviation															
0000-0600	0,3	0,6	0,9	1,9	0,7	5,6	2,6	0,2	2	2	1	2,3	1,7	1,4	1,3
0600-1200	0,6	0,5	0,3	1	1,9	1,9	0,7	0,3	1,5	0,6	1	3,2	1	0,8	0,4
1200-1800	1,3	1,9	1,2	3,4	0,4	0,8	0,6	0,9	5,6	1,5	2,1	0,9	0,7	1,2	1,7
1800-2400	1,3	0,4	1,1	4,4	1,5	2,4	1,3	0,9	2,1	0,7	3,7	2,1	1,7	0,6	1,7
% Temp gradient															
deviation															
0000-0600	3,9	5,1	1,4	4	4	6,4	3,6	3,3	5,7	16,2	4,9	3,3	5,2	3,7	14,2
0600-1200	8,3	3,4	3,3	7	7,5	4,9	6,8	4,2	12,1	3	9,6	14,2	14,3	7,3	17,2
1200-1800	5,9	2	1,6	7	1,3	5	1,9	4	22,1	3,5	9,9	5,3	5,7	11,6	3,2
1800-2400	3	2,1	5,7	3,5	5	3	3,8	1,7	7	4,6	8,1	9,9	5,1	3,2	4,7

Table1. This shows percentage deviation over 6 hour periods of the variables used in the AROME Arctic based altitude correction algorithm. Deviation is calculated as maximum minus minimum value for the day and period.

For each dataset presented in Fig. 3 we have calculated the Standard Deviation of the Mean (SDOM), i.e. a 67% expectation for the deviations of the means of our results. We have seen that the SDOM varies typically between 25 – 30 meters, which means that any persistent deviation greater than 100 meters is likely to be due to variations that we haven’t included in the model. We are typically observing persistent variations of around 100 - 200 meters. This may be caused by lasting local meteorological and geographical pressure variation effects away from normal which we have not included. Another plausible explanation is oversimplification when obtaining the observed temperature gradient. Variations in the mean taken over a few hours are likely to be due to temporary inaccuracies in AROME Arctic atmospheric predictions, such as cloud cover and/ or strong winds, causing fast changes in variables, such as those indicated in table 1 for day 9. Horizontal winds may cause timing uncertainty for the prediction. Variations in the mean over time spans less than an hour are likely, and may be due to unpredictable fast changes in weather conditions. There may also be systematic errors in the raw radar data reports from particular targets due to incorrect calibration of barometer. We have attempted to average out most of these fast changing effects in this paper by not considering durations of less than one hour.

As with the regression method we expect fewer days of successful predictions in unstable summer conditions, but the difference is that in the AROME Arctic based method this may be predicted by producing Table 1. It is a main advantage of the AROME Arctic based method that it may be used to produce variables which indicate fast changing atmosphere and

indication on temporary increased uncertainty and less trust on the prediction model. An operational system will require that the meteorological model produces such a continuous measure of service quality. Another advantage of the AROME Arctic method is that it uses a physical and dynamic prediction model, and not ‘next period will equal parameter estimation period’.

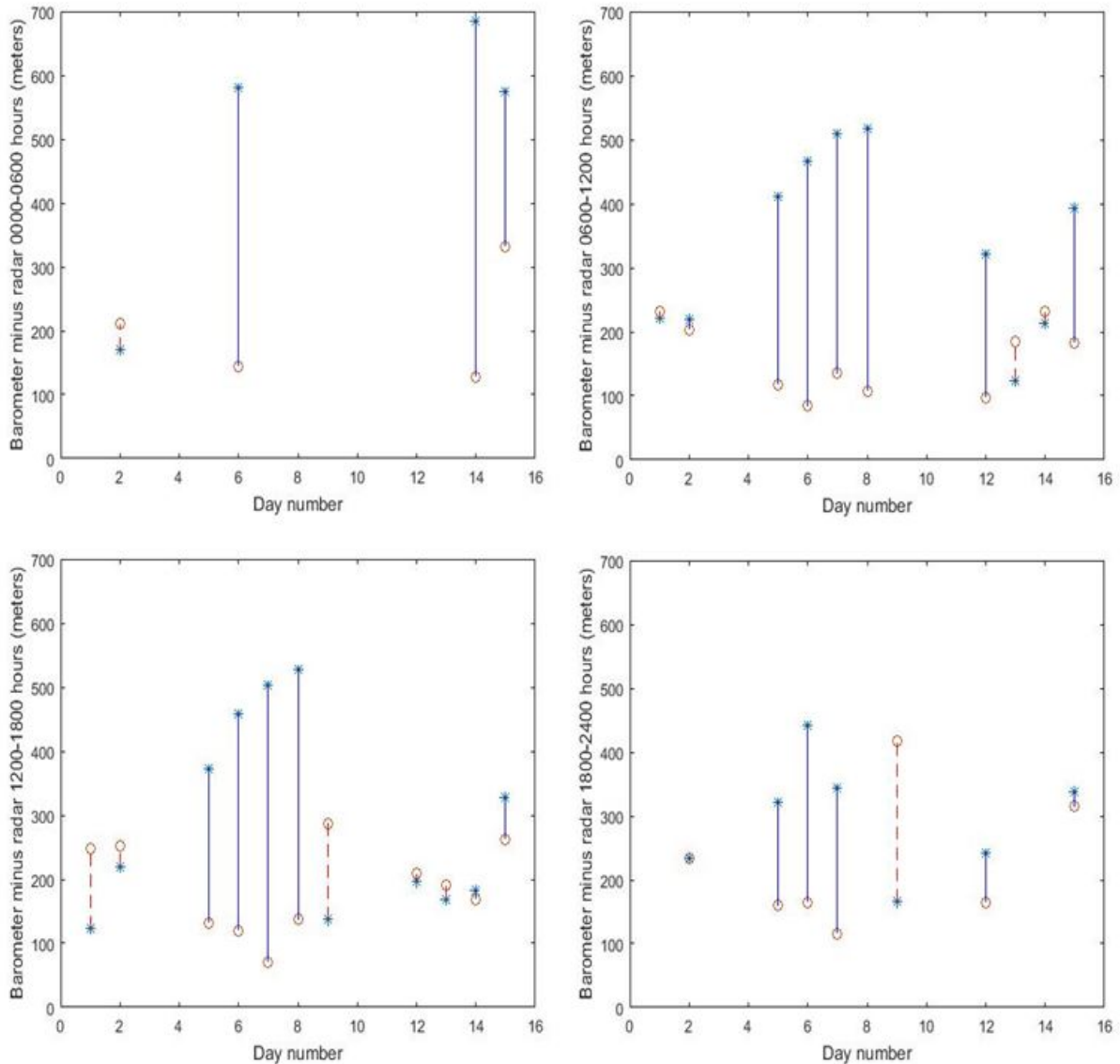


Figure 3 Results of applying barometer and radar corrections are shown as decrease or increase of absolute value of barometer minus radar altitude. A value close to zero indicates perfect match of barometer to radar altitude. The ‘*’ indicates value before corrections are applied, and the ‘o’ indicates after correction. Solid line indicates improvement, and dashed line indicates worsening.

6. Conclusions and suggestions for improvement

In section 4 we suggest a straight forward and simple regression method. Considering the results shown in sections 4 and 5, using the physical AROME Arctic forecasting model is clearly improving the averages accumulated over long time and many targets.

Without the need for GNSS data we have promoted a method which improves the estimate of the averaged difference over many samples between barometric and radar altitude. In tracking air traffic one is not really interested in knowing the precise geometric altitude. It is more important to be able to improve the comparison of data from different sensors, in order to verify tracks and discover non-cooperating targets. Independence of satellite is a bonus.

However, in an operational system for tracking of targets, we would require very dense space and time specific information from AROME Arctic. This information is already present in the AROME Arctic model as is from the Meteorological office, but software should be developed for fast retrieval of data for online processing with airplane targets. Meteorological data from layers closer to sea level should be incorporated in future analysis, which is strongly recommended by [6]. We might also wish to improve the AROME Arctic model by using meteorological measurements such as available data from observed airplanes' meteorological registry, which really may be treated as meteorological measurement stations.

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