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Using atmospheric weather models to improve radar measured altitude

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Summary

This report discusses how the atmosphere affects radar and barometric measurement of altitudes of airborne vessels. One may transform each kind of measurement to a corrected dataset in units of meters using atmospheric predictions.

Calibration of barometers are relative to mean sea level and ‘standard atmosphere’. By employment of a weather-modelled relationship between latitude, longitude, barometric calibrated pressure and geometric height in units of meters, barometer pressure converts to correct reading in meters.

Radar beams bend through the atmosphere due to a vertical refractive index gradient. If weather predictions are unavailable, the standard so-called ‘effective earth radius’ compensation is usually employed, which corresponds to a ‘standard’ constant refractive index gradient. We compare usage of this constant to employing an averaged weather predicted refractive index gradient between radar and target.

We also make calculations for illustration of the effect of relative positioning of radar and air vessels at different altitudes and distances. At long distances between radar and observed air vessel we find that use of atmospheric prediction data correction often means the order of 1000 meters less subtraction of altitude than by using ‘standard’ refractive index gradient correction, i.e. the altitude of the air vessel is in reality up to 1000 meters higher. In general, a large error and difference between barometric and radar based measurement is present if actual atmospheric conditions are not accounted for.

Sammendrag

Denne rapporten diskuterer hvordan atmosfæren påvirker radarmålinger og barometriske målinger av luftfartøys høyde. For å kunne sammenligne radar- og barometermålinger regnes de begge om til geometrisk høyde i meter ved å ta hensyn til atmosfærens tilstand.

Barometer er alltid kalibrert i forhold til middels havnivå og «standard» atmosfære. Et væravhengig modellert forhold mellom breddegrad, lengdegrad, barometrisk trykk og geometrisk høyde i meter benyttes til å finne mellomliggende verdier og gjøre direkte oppslag fra trykk til riktig antall meter over havnivå.

Radarstråler avbøyes gjennom atmosfæren på grunn av en vertikal gradient i brytningsindeks. Hvis værdata ikke er tilgjengelig, er det vanlig å bruke en «effektiv jordradius» i radardekningsberegninger som er lik 4/3 multiplisert med egentlig jordradius. Dette tilsvarer en «standard» konstant brytningsindeksgradient. Vi sammenligner effekten av å bruke denne konstante gradienten i forhold til effekten av å beregne den aktuelle gjennomsnittlige værpredikterte brytningsindeksgradienten.

Vi utfører så beregninger for tenkte relative plasseringer av radar og luftfartøy. Ved lang avstand mellom radar og observert luftfartøy ser vi at bruk av atmosfæredata kan gi opptil 1000 meter mindre fratrekk i høyde, som betyr at luftfartøyet at luftfartøyet er 1000 meter høyere oppe enn det som beregnes ved bruk av «standard» brytningsindeks. Bruk av «standard» brytningsindeks vil derfor i mange tilfeller gi en stor feil og forskjell mellom barometerbasert og radarbasert høydemåling.

Contents

Preface

The studies referred to in this report were initiated after a visit to a radar site where displays were showing disagreement between primary radar and secondary radar flight altitude. The observations required explanations, and subsequently scientific papers giving reasons for the deviations were investigated. All papers found referred to effects when atmospheric conditions are different from ‘standard’. By employing known mathematical procedures as well as weather forecasted parameters, appropriate corrections to altitude measurements were successfully made and documented in a published paper. The current follow up report is providing more detail on the treatment of the atmospheric data and suggestions for further improvement.

Kjeller, 12 March 2020
Walther Åsen

1 Introduction

Wireless surveillance, communication and navigation signals are carried by electromagnetic waves which pass through the atmosphere. Electromagnetic wave propagation models for different weather, manmade obstacles and terrain are well established and further developed over many decades and used in combination with very detailed terrain maps. However, 3-D dynamic model descriptions of atmospheric weather conditions of high precision and accuracy have only been around for a few years. The inclusion of a large number of new terrestrial and space technologies for atmospheric weather sensing, as illustrated in fig. 1.1, in conjunction with the development of new complex atmospheric weather prediction models, have paved the way for accurate and precise modelling of the atmosphere as a 'lens' for electromagnetic waves. By using weather predictions of high accuracy and density in 3-D space we will show how this information may be utilized to increase the accuracy of both primary radar altitude measurements and secondary radar pressure altitude reports.

For the purpose of illustration we will in this report be referring to and using results from runs of the numerical weather prediction model 'MetCoOp Ensemble Prediction System' (MEPS), which are distributed openly on the Internet by the Norwegian Meteorological Institute (MET Norway). The MEPS is an operational model since November 8th 2016, and various parameters of the model are verified against measurements in quarterly reports from MET Norway. MET Norway, Swedish Meteorological and Hydrological Institute (SMHI), and Finnish Meteorological Institute (FMI) are continuously cooperating on running and developing the model. According to [1] the model output covers large parts of the Nordic countries, with a horizontal resolution of up to 2.5 km and 65 vertical layers always. The vertical discretization is approximately 15–100 m up to 1 km, but with decreasing discretization up to an altitude of approximately 33 km. Fig. 1.2 shows the coverage area made freely available by MET. The model includes modelling of many more parameters than we shall be concerned with in this report, and interfaces with and uses data from other models, such as the 'European Centre for Medium-Range Weather Forecasts Integrated Forecasting System' (ECMWF-IFS). It exploits input from an increasing number of sensor sources, for instance satellite systems and aeroplanes. One of the main advantages of MEPS versus ECMWF-IFS is the more detailed modelling in mountainous terrain in Norway. See reference [1] for more details.

The main specification of the atmospheric 'lens' is given through three basic physical parameters of the MEPS model: a three dimensional representation of dry air pressure, water pressure and temperature. Due to gravity the atmosphere is thicker near the ground and the effects of terrain is also very important at low altitude. This makes it difficult to make good point estimates of the refractive index and its gradient at low altitude. Additionally, the density and shape of the 'lens' is time dependent, and rate of change depends on wind strength.

The theme for discussion in this report is limited to ground based long range radar applications, for which average refractive index gradient between radar and target is more important than point estimates, since the expected variance of refractive index gradient at a particular point becomes less important over long ranges. However, in order to get a measure of how much we trust the weather predictions we need to characterize the predicted dynamics of the atmosphere. For that purpose we may calculate standard deviations of refractive index gradient over forward predictions for the area of interest.

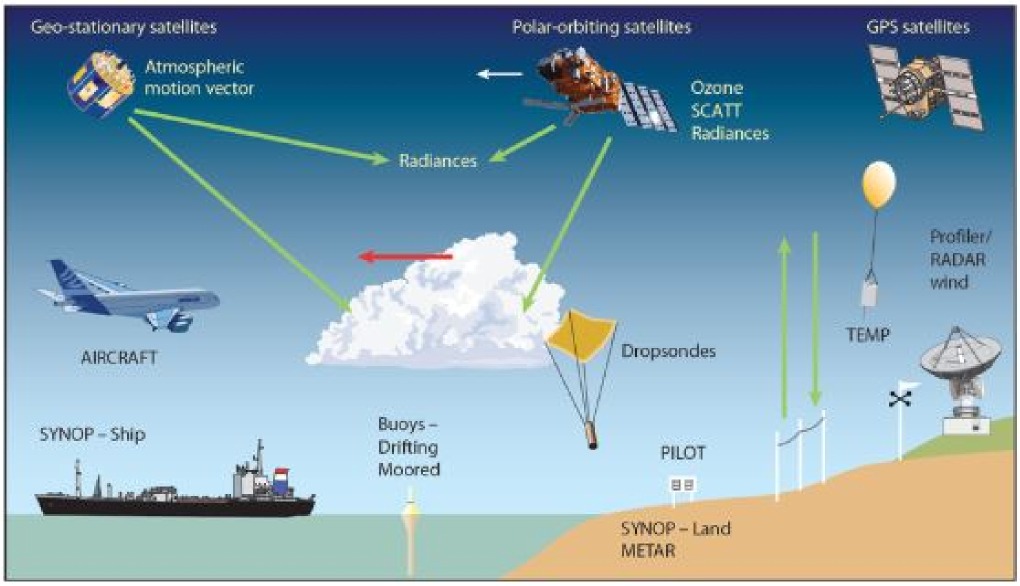

Figure 1.1 Copied ECMWF illustration of meteorological data sources

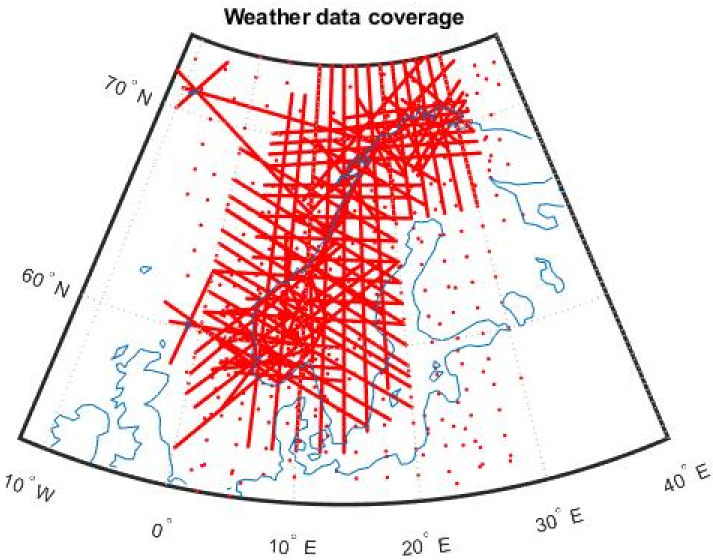

Figure 1.2 Plotting of MEPS data point grid available from MET

All basic physics of the atmosphere and mathematics referred to in this report is based on standard procedures.

The atmospheric model is of course not only useful for communication, navigation and surveillance in the electromagnetic wave propagation context, but also for practical navigation routing over sea, on land or in the air, in order to avoid foul weather. In particular, for aeronautical navigation, one might wish to find an optimal routing for minimum turbulence, lowest fuel consumption, fastest route or safest route. We will not discuss any such applications in this report, but instead restrain ourselves to the altitude part of tracking aeronautical objects. Once geometric altitude is established from primary and/or secondary radars, these may be compared and used by a tracker, for instance to improve a track or to make a decision whether two differently measured altitude results originate from the same object.

2 Using an atmospheric model for obtaining altitude of air vehicles

One might argue that in many countries air traffic is not dense and there are few cases where 3-D position data of air vehicles need to be resolved. However, there is a worldwide increased demand for applications which depend on available airspace at different altitudes. Many of the new platforms will constitute a mix of large and smaller unmanned and manned airspace users. Today, flight plan conflicts are primarily resolved by assigning different 'Flight Levels' (FL) to different flights. The 'Single European Sky' (SES) initiative by the European Union (EU) foresees by 2035 the attendance of unmanned platforms at all atmospheric altitude levels. Also, the SES vision is to make 3-D flight plans, discontinuing the current policy of making 2-D flight plans, with FL being used for conflict resolution.

The meteorological MEPS model is particularly useful for obtaining precise geometric altitude by

- receiving reports of pressure altitude from the airborne object/target
- non-cooperative radar measurement of target altitude

2.1 Converting pressure altitude to geometric altitude

Obtaining longitude and latitude position coordinate by Global Navigation Satellite Systems (GNSS), such as GPS, provide very accurate longitude and latitude, but somewhat less accurate geometric altitude referred to earth surface. However, the lower accuracy of geometric altitude is not the reason why elevated platforms refer to FL pressure surfaces for altitude. The reason is the need to avoid confusion in use of different geometric height conversion methods which might potentially lead to mid-air collisions. Instead, basic navigation reference is barometer with ‘standard atmosphere values’, calibrated to 1013.25 hPa air pressure at ‘Mean Sea Level’ (MSL) of 15.0 °C temperature, and -1.98 °C per 1.000 feet temperature lapse rate (up to 36.000 feet). Civilian or military Secondary Surveillance Radars (SSR) send requests to targets and expect to receive such pressure altitudes as responses.

However, in order to compare these pressure altitudes with altitude data from other types of sensors, such as radar, one needs to convert to geometric altitudes relative to earth surface. A standard conversion table may be used to convert to geometric altitude, and then adding a correction factor using actual temperature outside the air vessel and at the Earth’s surface. The accuracy of this method relies on the temperature lapse rate being constant and the temperature measurement at the airborne object and ground being correct.

A much easier way, which also seems more robust, would be to use the time dependent weather model which produces an output such as the one in fig. 2.1,   and interpolate the output to find the correct geometrical height at the 3-D (lat/lon point number + altitude) pressure point. Latitude and longitude coordinate combinations of fig. 2.1are given a number for each pair (lat/lon point number) to reduce the number of dimensions.

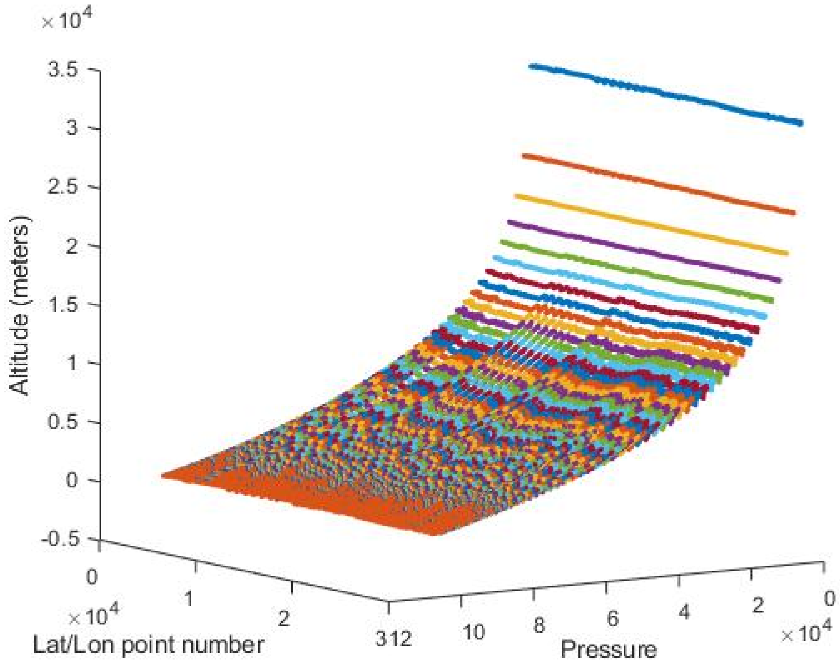

Figure 2.1 Model snapshot of the state of the Pressure (hPa) – Altitude (meters) relationship at 15th of October 2019 at 18.00 UTC. Atmospheric corrections to radar measured altitude of air vehicle.

2.2 Correcting measured primary radar altitude for atmospheric conditions

Primary radars operate non-cooperatively against targets and produce estimates of target altitude. This altitude needs to be corrected for the vertical altitude dependent refractive index gradient of the atmosphere given by Snell's law. Usually, if no atmospheric data are available, a so-called '4/3 earth radius correction' is applied, which means that the influence of the atmosphere is accounted for by increasing the radius of curvature of Earth in calculations by a factor of 4/3.

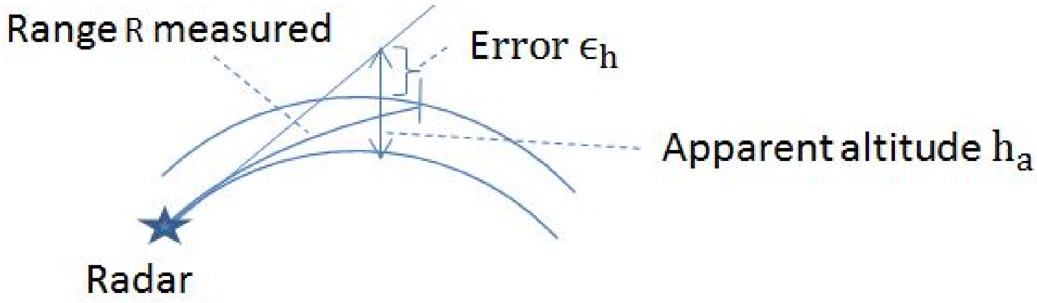

Figure 2.2 An (exaggerated) illustration of error in radar measured target altitude due to vertical rate of change of refractive index.

With an atmospheric model being available, the vertical refractive index gradient may instead of using a constant number be computed directly from the first derivative of the refractive index, which is a function of the model variables dry air pressure, humidity and temperature.

According to [4], 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 Equation 1:

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

Using calculus of differentiation, denoting 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', leads to Equation 2:

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

See [2] and [3] for more details.

Paper [2] takes the reader through a set of simplifying assumptions which end up with Equation 3, which concludes that the appropriate correction ϵ_h [m] to radar height measurement is approximately equal to a geometry factor multiplied by the average refractive index gradient n' [m^{-1}] for the path between radar and the object observed. In Equation 3, R [m] is the distance measured and h_a [m] is the apparent radar height measured.

$$\epsilon_h = \frac{(R^2 - h_a^2)^{3/2}}{2R} n' \quad \text{(Equation 3)}$$

In addition to ϵ_h there is also a (very small) error in measured range.

2.2.1 Refractive index gradient variations

By inspecting MET data curves we find quite large changes in refractive index gradient over time and place, particularly below 5.000 meters of altitude, see fig. 2.3 and fig. 2.4. However, the average values over many samples should be fairly stable, so our hypothesis is that the variations should be somewhat smoothed for a calculated average refractive index for a long path between radar and target.

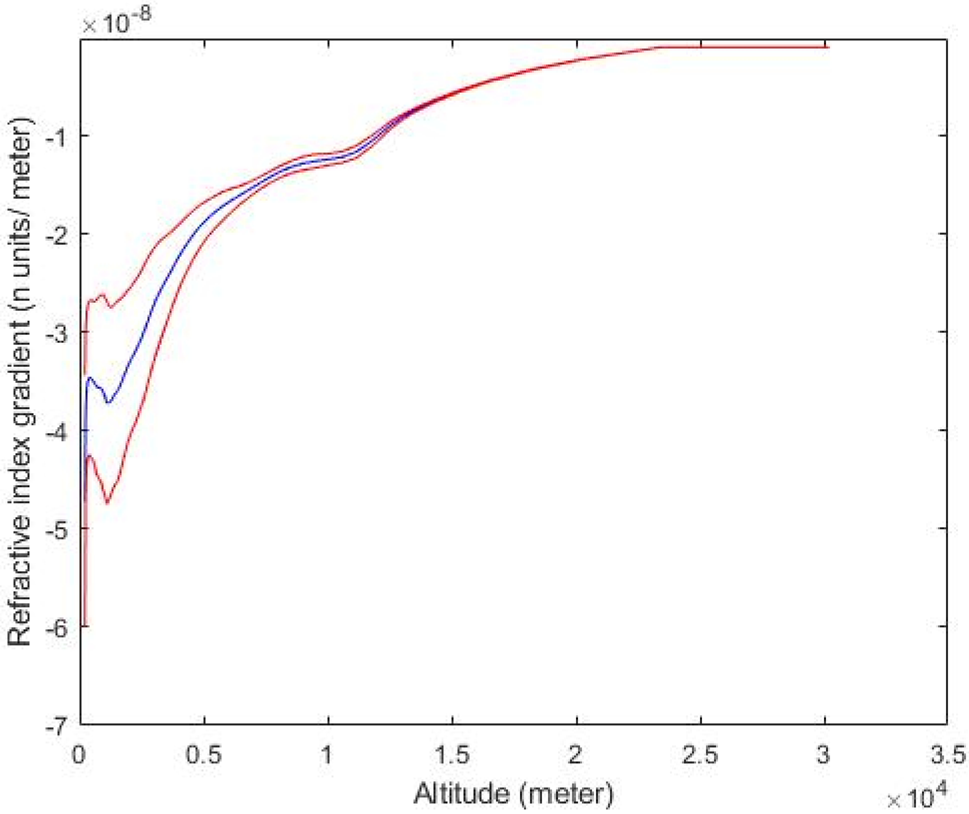

Figure 2.3 Blue line shows mean of refractive index gradient for each position over 1–19 hours of predictions for entire modelled area, from 15th of October 2019 at 18.00 UTC until 16th of October at 13.00 UTC. Red lines show mean +/- variations (mean of standard deviations) over the 19 hour predictions.

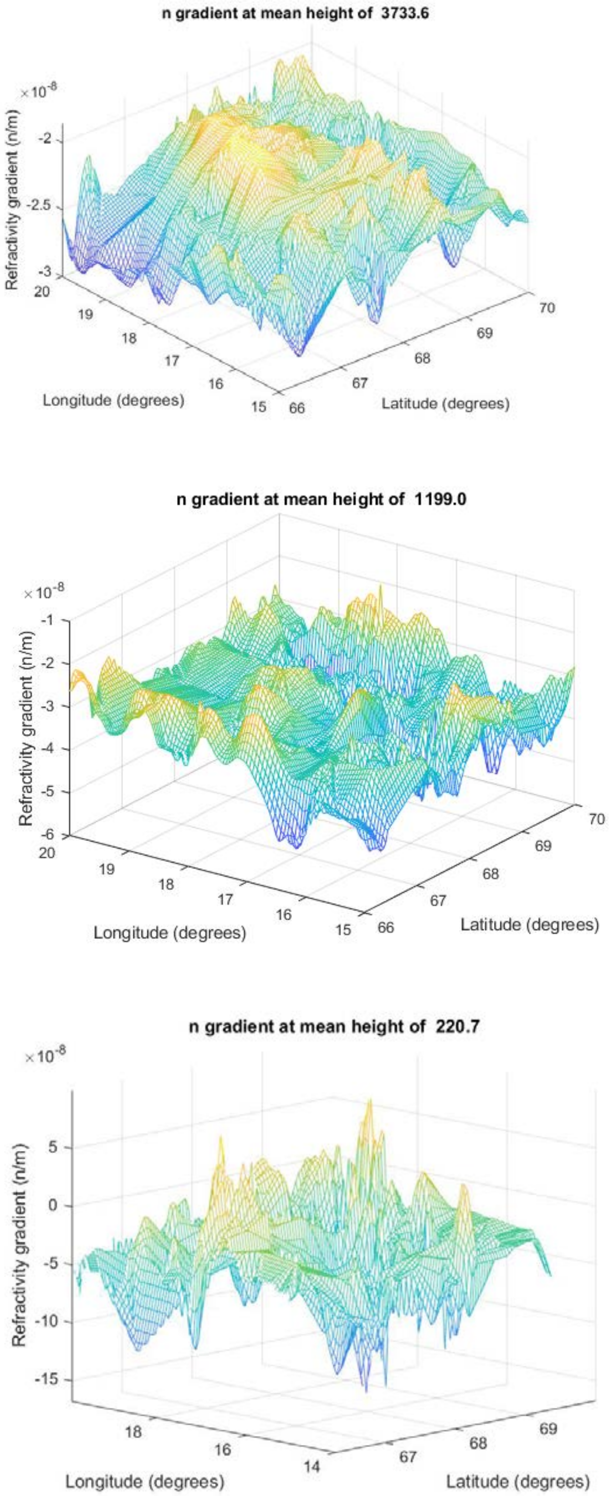

Figure 2.4 Typical refractive index gradients over an area of size approximately 500 km by 500 km, and at different altitudes in meters (3733.6, 1199.0 and 220.7 meters), met data prediction 15th of October 2019 for the hour 18.00–19.00 UTC

2.2.2 Modelling horizon limited range

Horizon limited *radar range* will be different for different target altitudes, depending on the effective (n' corrected) earth radius.

The effective earth radius factor *k* relates to refractive index gradient n' by

$$k = \frac{157.0}{157.0 + n' 10^9} \quad \text{(Equation 4)}$$

The percentage decrease/increase of range relative to the standard $k = 4/3$ is then

$$p = 100\sqrt{\frac{k}{4/3}} = 100\sqrt{\frac{\frac{157.0}{157.0+n'10^9}}{4/3}} \quad \text{(Equation 5)}$$

An example of use of this relationship of Equation 5 (plotted in fig. 2.5) would be: Assume a target at low altitude and range is range limited by earth curvature. If the actual refractive index gradient is $n' = -2.X\ 10^{-8}\ n/m$, then the range is, by Equation 5, only 90 % of the range given by 4/3 earth radius correction. This occasional reduction in radar range is important to be aware of.

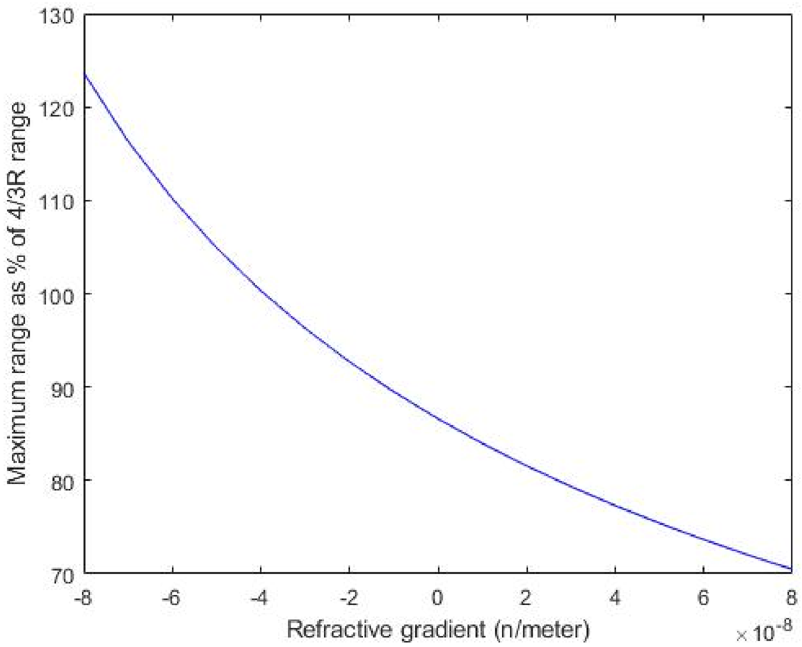

Figure 2.5 Plot of Equation 5: Range as percentage of standard (4/3 earth radius model) refractive index gradient range, plotted for different average refractive index gradients

2.2.3 Modelling correction of target altitude by using refractive index gradient data

Starting from Equation 3 we calculate n' from MET data. We proceed by simulating the other parameters without using any actual radar or barometer measured altitude data.

We will ignore terrain effects on signal path between radar and target. In Norway typical mountain sites for radar would be between 700 and 1.000 meters of altitude. Most commercial flights operate at around 11.000 meters of altitude, but flights of interest may be at altitudes in the range between 3.000 and 12.000 meters. Some special aircraft may operate as high as 20.000 meters. We will be interested in radar range **R** from 0 to 500 km. From Equation 3 we see that the correction term increases approximately proportionally to R^2. Thus, an object around 100 km away will only result in about 4 % of the correction at 500 km distance.

As previously discussed, flights are not really referred to geometric altitudes, but to pressure levels. Even so, in our analysis we will refer to $\mathbf{h_a}$ at defined geometric altitudes. The outcome of the modelling will be corrections $\boldsymbol{\epsilon}_\mathbf{h}$ to the $\mathbf{h_a}$ values, and these values will be compared to those calculated, using $n' = 3.9X10^{-8}\ n/m$, commonly nicknamed the standard 4/3 earth radius correction factor.

The standard 4/3 earth radius model is really intended for use as an average value below 1 km of altitude only, and will therefore not be expected to be representative for radar paths higher into the atmosphere. In reality the (negative) gradient is often closer to zero than the standard value against higher altitude targets, and radar ray bending is therefore less than the standard value, although not necessarily so for low altitude targets. Generally, the relaxation of ray bending relative to 4/3 model is supposedly largest at long distances from radar and at high target altitudes.

2.2.4 Examples of calculated altitude corrections for radar altitude measurements

We will now demonstrate effects on the performance of a hypothetical radar against a target arbitrarily positioned, using real weather predicted refractive index gradients valid for a particular area and time. The time period used is indicated in the headings of the subchapters of this chapter. Terrain and propagation effects by terrain obstacles are ignored, as we are solely interested in the atmospheric effects. For the sake of calculations the radar is arbitrarily situated at 1.000 meters altitude, 20 degrees longitude and 70 degrees latitude. The target is at latitudes 65.9 to 69.9, in steps of 0.1, paired with longitudes at 15.9 to 19.9, so that the path distance from radar to target varies from a few kilometers to about 500 kilometers. The target altitudes chosen for the calculations are at 5.500 meters, 11.000 meters and 20.000 meters.

Fig. 2.6a to 2.14a show the results of two alternative refractive index gradient calculations for the different radar–target ranges. The red dotted line show, for each position of the target, the refractive index gradient by calculating refractive index at target minus refractive index at radar and dividing by the height difference between target and radar. The blue curve is obtained, for each position of the target, by calculating the gradient in small steps along the path from radar to target and calculating the average gradient.

The curves of fig. 2.6b to 2.14b show three alternative altitude corrections to be applied, by employing Equation 3. The green line is produced assuming the standard 4/3 earth radius correction, $n' = -3.9X10^{-8}\ n/m$. The red starred line is produced by estimating refractive index gradient as target refractive index minus refractive index at radar and dividing by the altitude difference between target and radar. The blue curve is obtained by assuming that the best estimate of gradient is the average along the path from radar to target. A very interesting feature of fig. 2.6b to 2.14b is that there is a large difference between the standard, the green curve, and the other curves already at 200–300 km distance from the radar. An interesting feature of fig. 2.6a to 2.14a is that none of the blue curves are reaching down to the standard 4/3 earth radius correction, $n' = -\ 3.9X10^{-8}\ n/m$. Of course, if the radar had been at lower altitudes and/or the target flying lower than 5.500 meters, this would be different. Another interesting feature is that at longer ranges the averaged curve falls below the simplified dotted calculation and thus comes somewhat closer to the standard value.

Fig. 2.8a, 2.8b, 2.11a, 2.11b, 2.14a, 2.14b show prediction estimates for a very high target cruising altitude of 20.000 meters. Such altitudes could for instance be held by military aircraft. These Figures indicate that using the standard altitude correction against these targets may, at long ranges, give a resulting altitude up to about 2.000 meters away from the true altitude.

In earlier studies [3] we applied a very simple method, using only the average refractive index gradient and a pressure to altitude conversion method in the neighborhood of a radar and target. We still managed to get the large area average differences between measured pressure altitude and radar measured altitude down from about 500 meters to about 100 meters. But, taking into account that the error is very small closer to the radar, an average difference of about 500 meters may indicate that the differences in practice are much larger at the highest radar observation ranges. Fig. 2.6b, 2.9b and 2.12b show predicted correction estimates for flights at normal cruising altitude of 11.000 meters for three different days. Taking into account that mountain shadowing of radar view is not considered, it seems plausible from these curves that, for all observations, the median difference between standard correction and estimated correction could well be roughly between 400 and 600 meters, which might be a good indication of agreement with conclusions in [3]. There was an apparent shortage in the argument for the claimed improvement factor of our previous work in [3] that we did not sort or analyze the improvements according to range. However, we are not interested in the range dependent precision of the radar with range. Instead we are very interested in the success of the weather forecast data in helping to improve the average performance of the radar output. Also, there is no need to obtain experimental proof of the effect of the atmosphere on electromagnetic wave propagation, as Snell's law of refractivity is a thoroughly studied and documented subject in physics. Also, independently from how trustworthy weather forecasts are, we strongly believe that the forecasts produced as examples in the current paper provide realistic data. Under these assumptions the method for radar altitude corrections and variations suggested, as well as for horizon limited range variations, demonstrates effects on radar measurements in realistic weather conditions. The correction method should accordingly be taken into account in radar performance evaluations.

2.2.4.1 Air target at altitude of 11.000 meter, 2019_06_28_1800

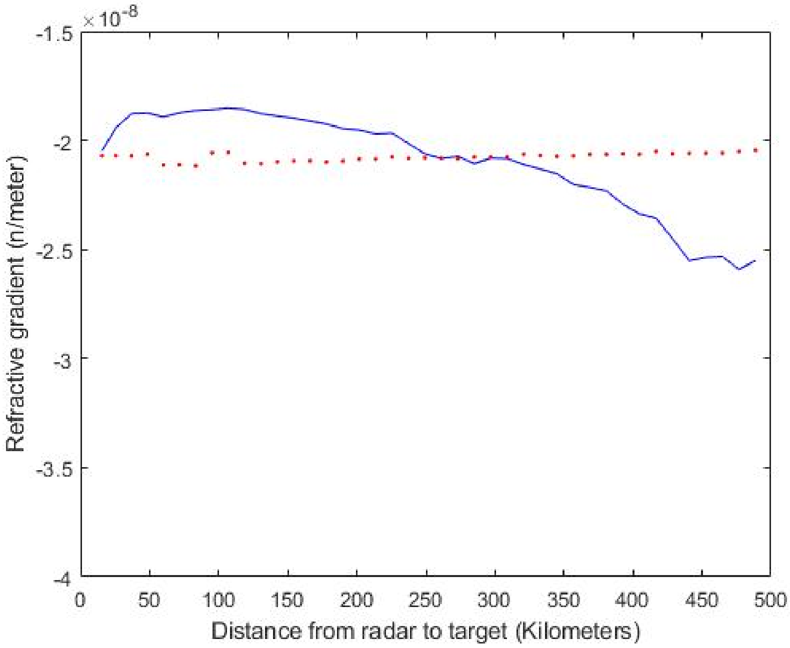

Figure 2.6a Refractive gradient

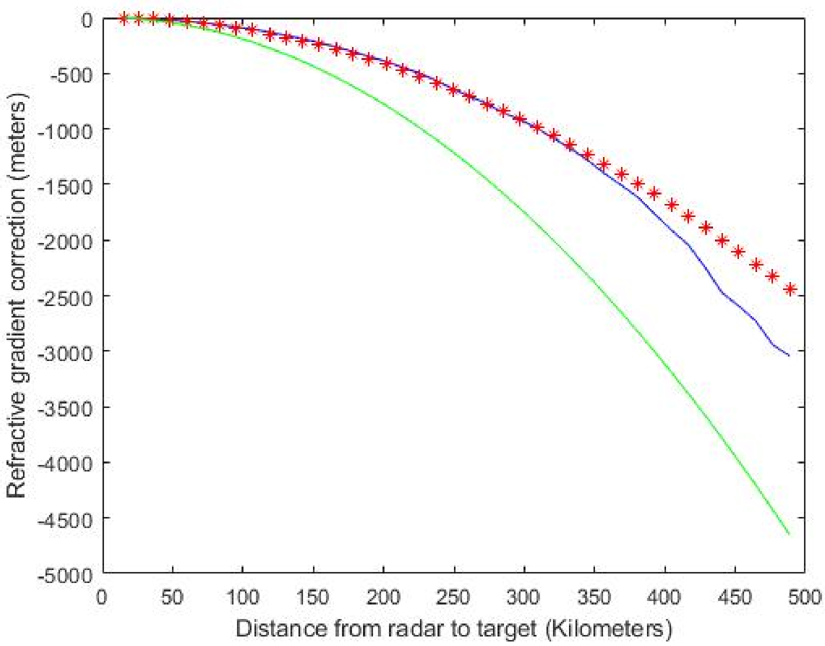

Figure 2.6b Average refractive index gradient correction as a function of distance from radar to target

2.2.4.2 *Air target at altitude of 5.500 meter, 2019_06_28_1800*

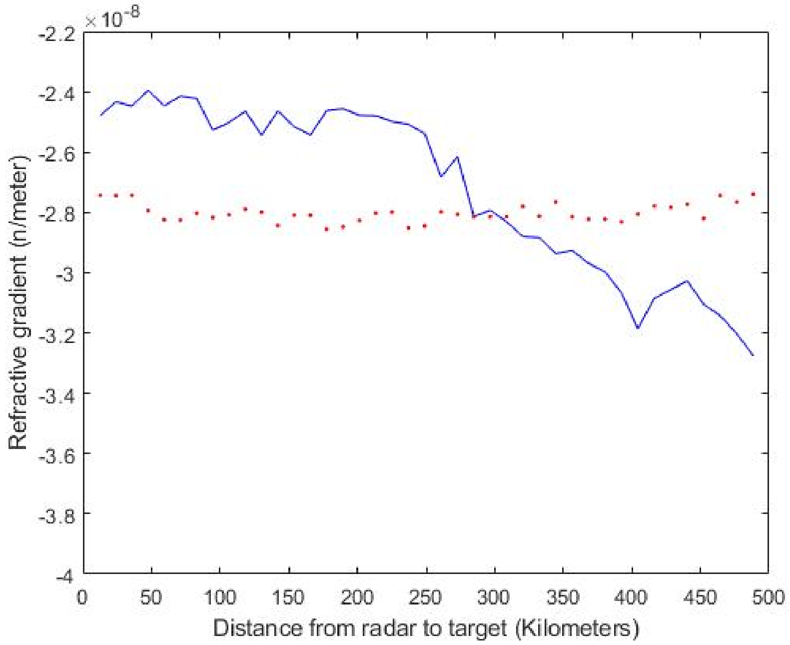

Figure 2.7a Refractive gradient

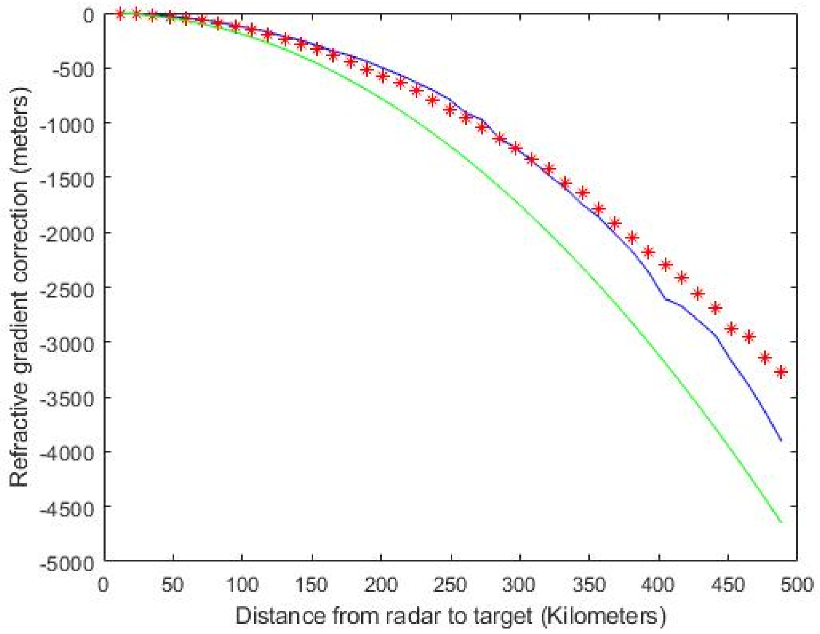

Figure 2.7b Average refractive index gradient correction as a function of distance from radar to target

2.2.4.3 Air target at altitude of 20.000 meter, 2019_06_28_1800

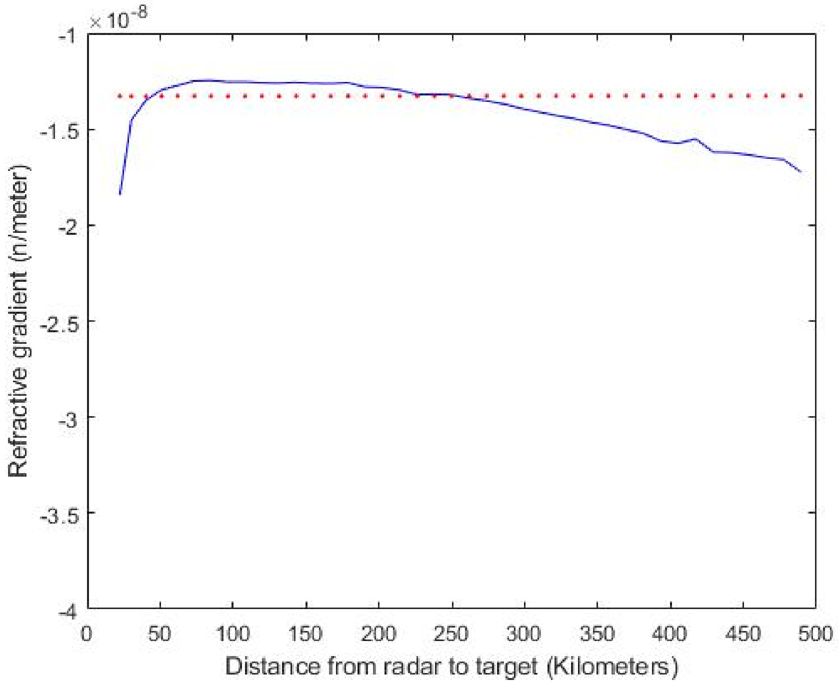

Figure 2.8a Refractive gradient

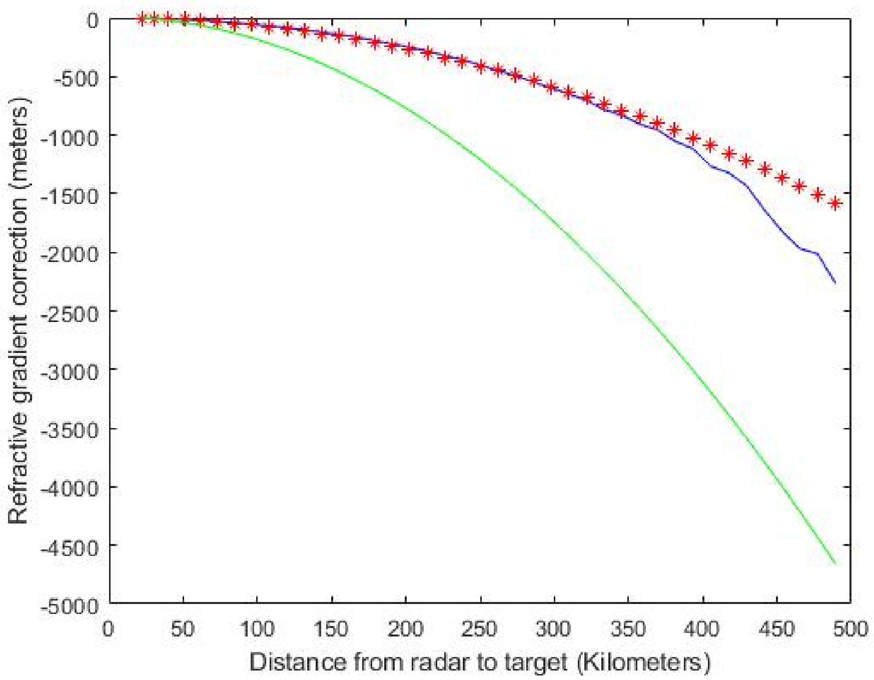

Figure 2.8b Average refractive index gradient correction as a function of distance from radar to target

2.2.4.4 Air target at altitude of 11.000 meter, 2019_07_11_0600

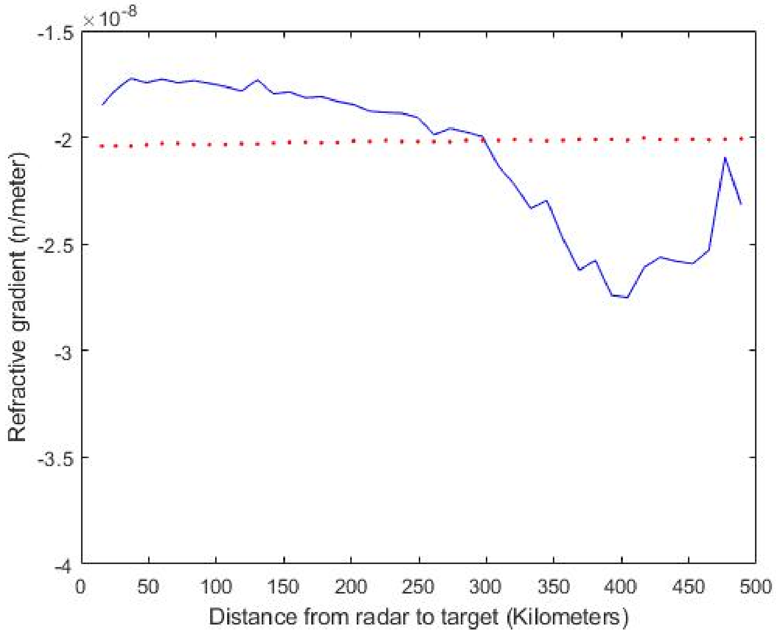

Figure 2.9a Refractive gradient

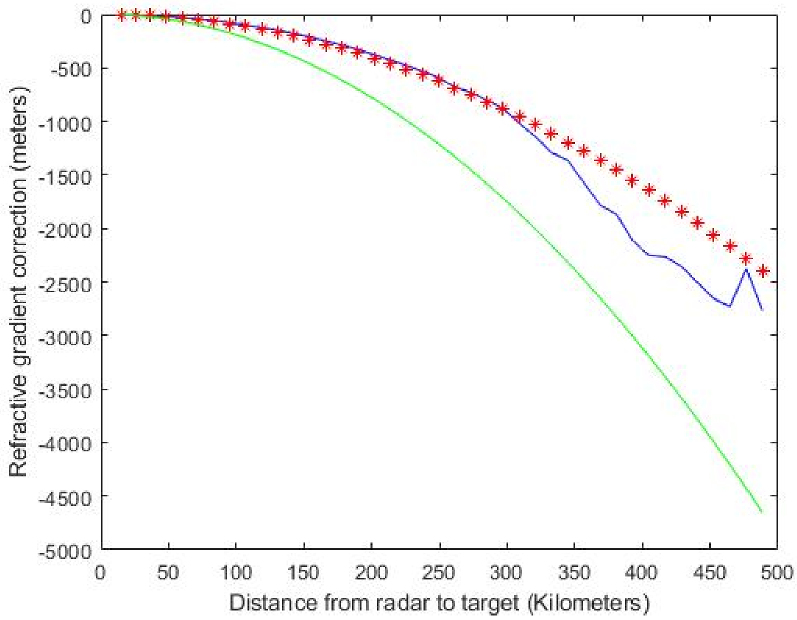

Figure 2.9b Average refractive index gradient correction as a function of distance from radar to target

2.2.4.5 Air target at altitude of 5.500 meter, 2019_07_11_0600

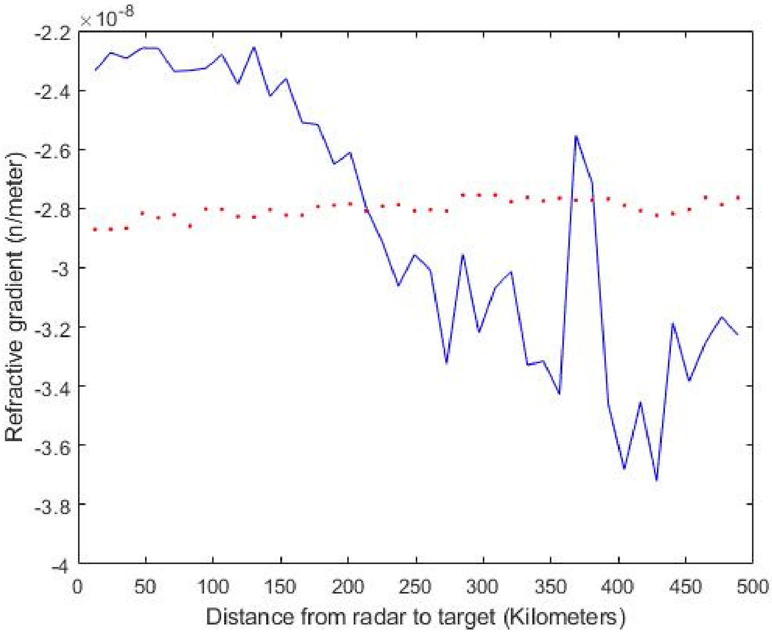

Figure 2.10a Refractive gradient

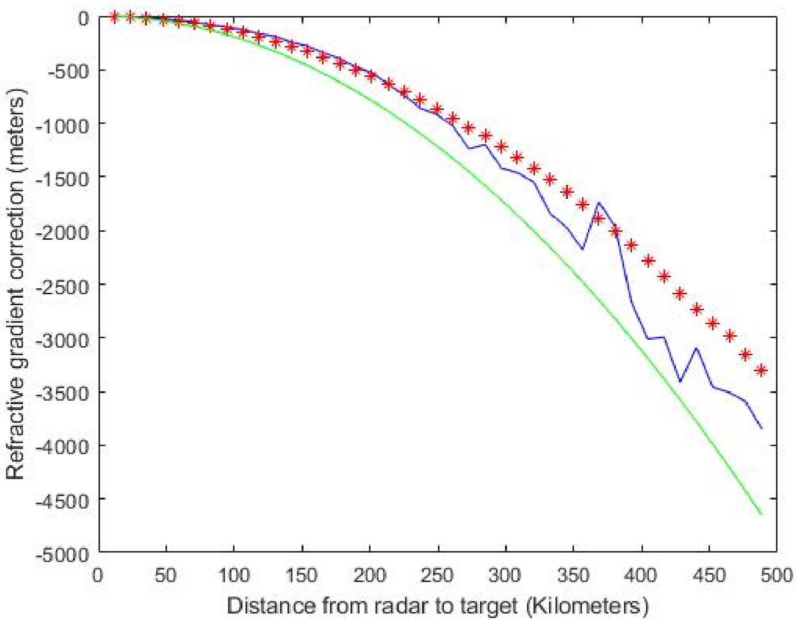

Figure 2.10b Average refractive index gradient correction as a function of distance from radar to target

2.2.4.6 Air target at altitude of 20.000 meter, 2019_07_11_0600

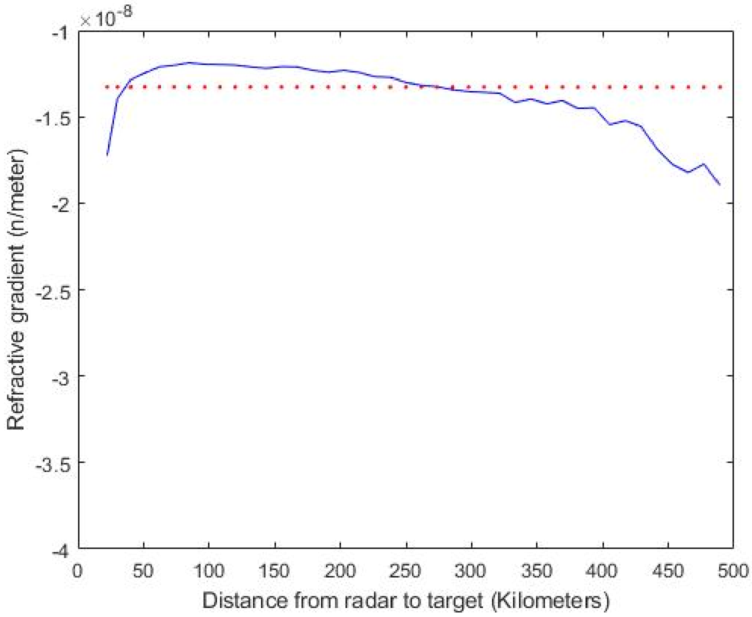

Figure 2.11a Refractive gradient

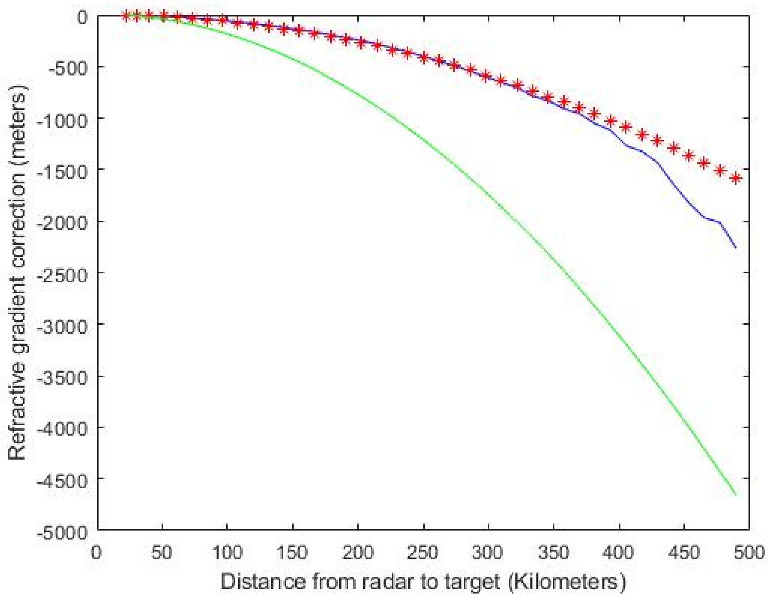

Figure 2.11b Average refractive index gradient correction as a function of distance from radar to target

2.2.4.7 *Air target at altitude of 11.000 meter, 2019_10_15_1800*

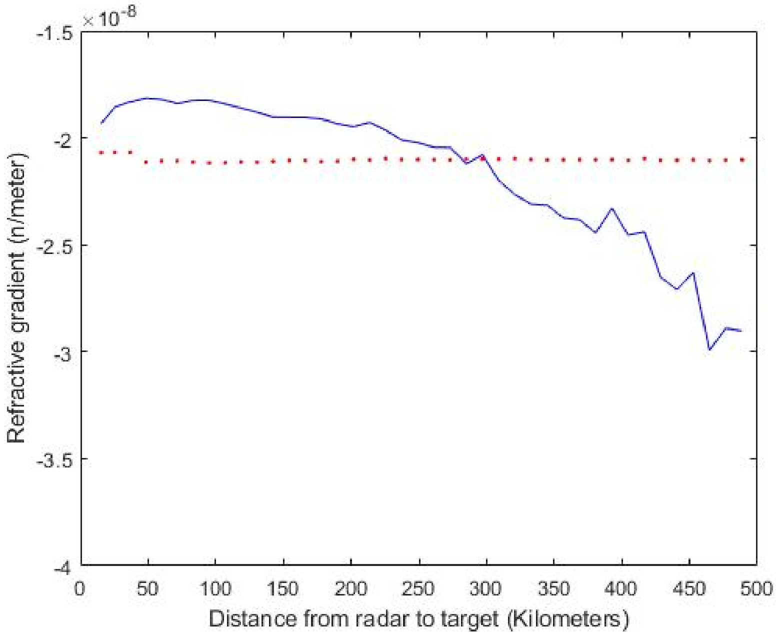

Figure 2.12a   Refractive gradient

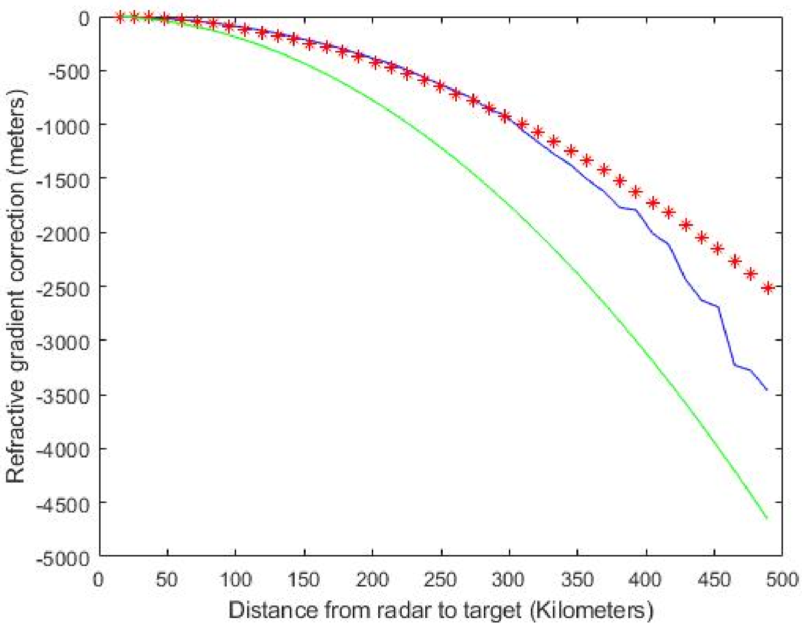

Figure 2.12b   Average refractive index gradient correction as a function of distance from radar to target

2.2.4.8 Air target at altitude of 5.500 meter, 2019_10_15_1800

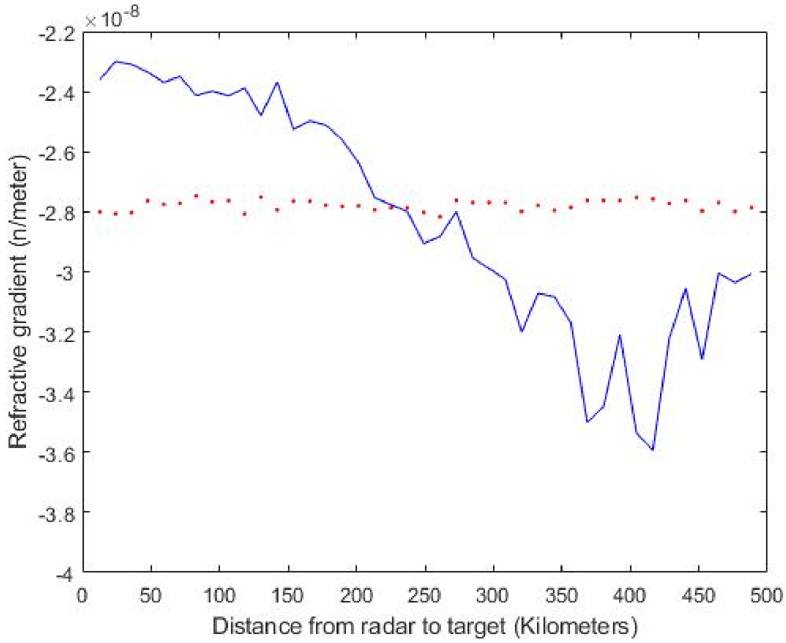

Figure 2.13a Refractive gradient

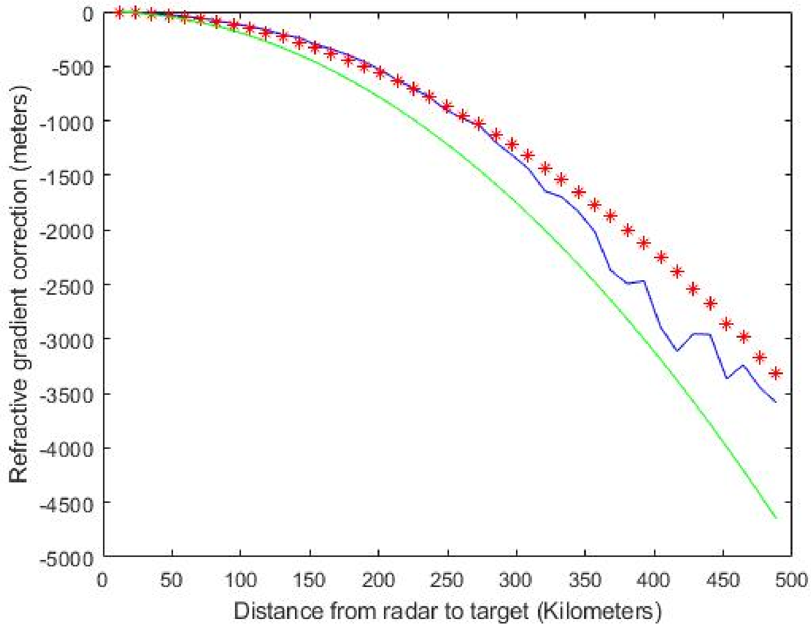

Figure 2.13b Average refractive index gradient correction as a function of distance from radar to target

2.2.4.9 *Air target at altitude of 20.000 meter, 2019_10_15_1800*

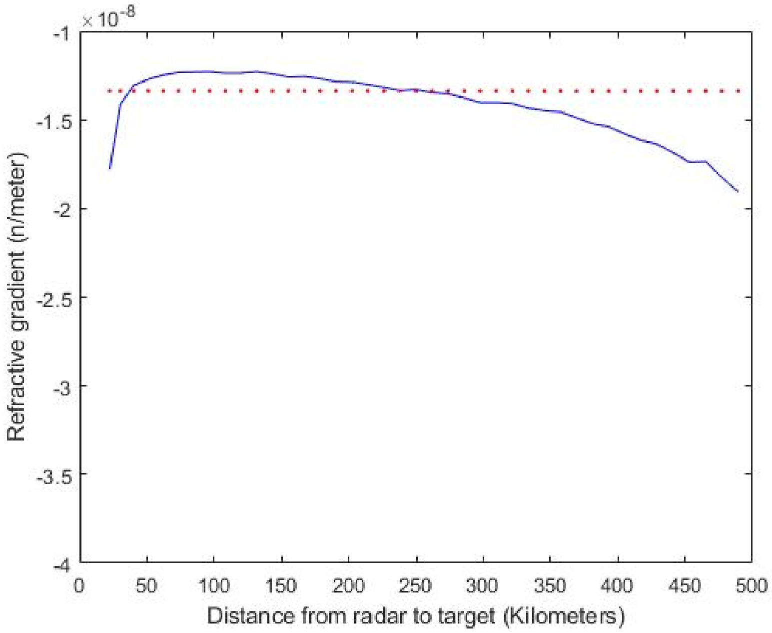

Figure 2.14a Refractive gradient

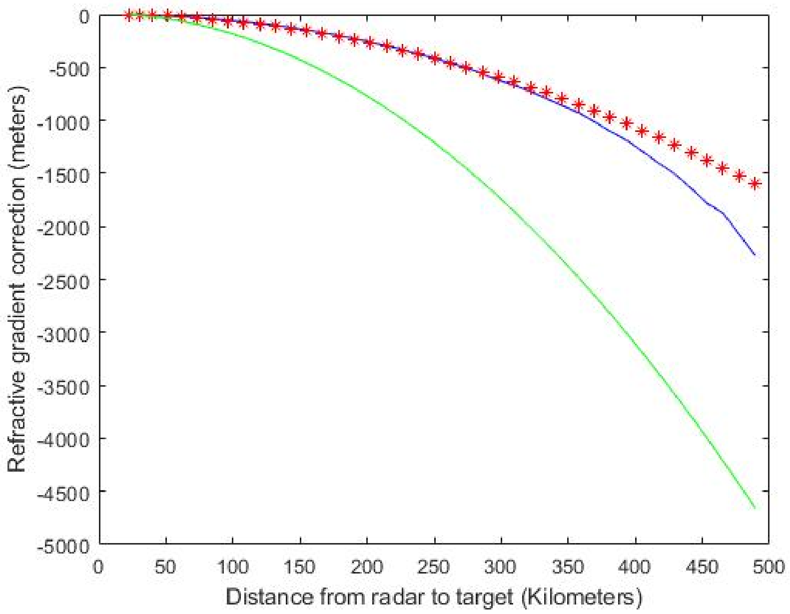

Figure 2.14b Average refractive index gradient correction as a function of distance from radar to target

3 Conclusions

Simple meteorology based radar altitude correction and pressure altitude correction methods were employed in a previous paper [3]. It concluded that, over large spans of time and space, initial mismatch between mean radar and pressure altitude of about 500 meters reduced to about 100 meters by making atmospheric corrections.

In this report we have investigated methods for calculating more detailed time, altitude and distance dependent radar altitude corrections. The new findings are more important at long radar-target distances and for altitude estimates of very high altitude targets. By employing actual atmosphere values rather than the standard ‘4/3 earth’ correction, we have illustrated that in many cases we may achieve an improvement of the altitude estimate in the order of 1000 meters. The method employed in this report is, as always, using Snell’s law of refractivity, but now taking into account all the locally forecasted atmospheric refractive index gradients instead of employing a radar site point estimate or a constant for the gradient.

Improved fit between secondary and primary radar altitude measurement will provide better air surveillance, increase ability to track air vehicles, and increase the probability of discovering air vehicles which deviate from their flight plans. Also, procurement of any particular 3-D radar system would benefit from a Site Acceptance Test which is taking local time varying atmospheric weather data corrections into account. This will increase the value of the evaluation and subsequent operation of the radar system.

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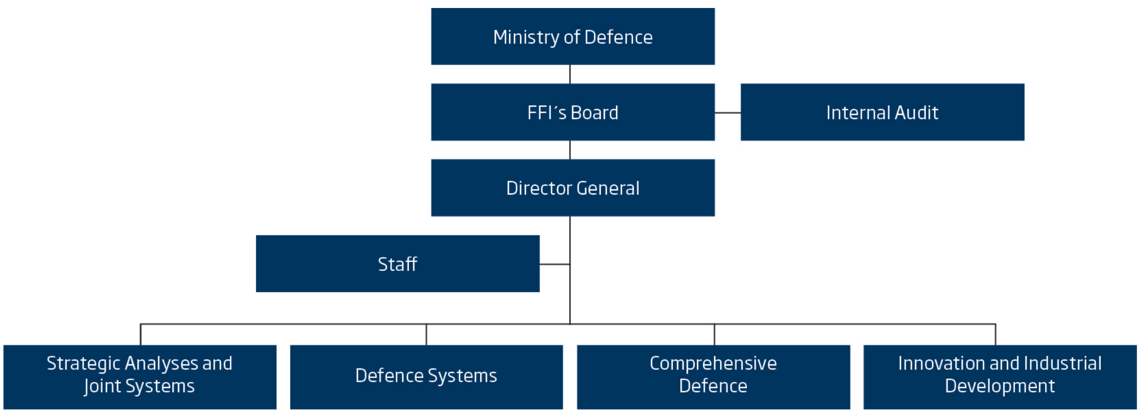

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