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Henrik Vedel

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Henrik Vedel
Danish Meteorological Institute *

Resumé.

We discuss the problem of converting the WGS84 geometric heights used by the providers of GPS derived atmospheric profiles to the geopotential heights widely used in NWP modeling and data assimilation.

Preparing data for the HIRLAM OI system this is found to be a three step procedure,

1 Conversion from WGS84 ellipsoid to EGM96 geoid geometric heights.

2 Extraction of the model surface geometric and geopotential heights from the model orography.

3 Conversion of the geometric geoid heights above the model surface to geopotential heights.

Step two makes the conversion model dependent. It is necessary because geopotential heights in the HIRLAM model are calculated as the sum of the model surface geometric height plus the difference of the geopotential height of the position in question and the model surface, a feature which is probably shared with many other NWP models.

The changes due to step one and three are found to be much larger than the model errors. The changes due to step two are smaller by an order of magnitude, being comparable to the model errors at higher elevations, but negligible over the sea and low terrain – areas covering a large fraction of Earth. It is tempting, though not directly advisable, to ignore it when preparing GPS profile data for HIRLAM OI analysis.

Expressions are given for the conversion of geometric heights to geopotential heights, both including and excluding the second step.

Even disregarding step 2 the transformation between geometric and geopotential height depends on both altitude and latitude. Neither dependence should be neglected.

Finally we notice that in a variational data assimilation system calculation of geopotential heights is not necessary prior to the assimilation procedure, and an expression for an observational operator providing the geometric height as function of pressure level is given.

*Address: Lyngbyvej 100, DK-2100 Copenhagen Ø, Denmark. Phone: (+45) 3915 7445. Email: hev@dmi.dk http://www.dmi.dk

The problem.

The GPS meteorological data vendors provide (almost) vertical atmospheric profiles of three types, namely the,

- bending angle,
- the refractivity,
- the pressure, temperature, and humidity,

as function of the geometric height relative to the WGS84ellipsoid. The degree of processing and the number of adopted assumptions increases down the list. (For a few more details on the GPS data-types, and their possible use in HIRLAM, see the two last sections of this note.)

Of these data-types, only the latter can by utilised in the current HIRLAM OI analysis system. Furthermore the OI system needs the data be provided either in the form of the geopotential heights of a number of fixed pressure levels, or as differences in geopotential height between (thicknesses of) such pressure levels.

The precision of the (pressure, temperature, humidity)-profile derived from the GPS data decreases towards the ground. It is therefore preferable and most robust to determine the geopotential heights from the geometric heights, rather than via the more highly processed pressure, temperature, and humidity data.

The WGS84 ellipsoid → EGM96 geoid geometric height transformation.

In the WGS84 ellipsoidal coordinate system the Earth is approximated by an ellipsoid generated by rotation around the minor axis of an ellipse centered on the Earth and aligned with its short axis along the geographic polar axis of the Earth. This ellipsoid provides a good analytical approximation to the Earth surface, and it is straight forward to transform between the Cartesian coordinate system used in the first stages of the reduction of GPS derived data and the ellipsoidal system.

The Earth surface itself is, however, highly irregular. These irregularities, which enter the NWP models in the form of the model orography and the altitude of the observational stations, are not specified nor measured relative to an ellipsoid, but relative to the geoid. Just as the heights on a normal topo-graphic map. The geoid is defined as the equipotential surface of the gravity potential at mean sea level. The undisturbed surfaces of the oceans are approximately equipotential surfaces, and the geoid can be described as the mean sea level surface extended across the continents (Handbook of Geophysics and Space Environments, [8]). The irregular surface and the density inhomogeneities inside the Earths crust make the geoid rise and sink, it is not rotationally symmetric and need be described by a map or a table.

The conversion from coordinates specified relative to the WGS84 ellipsoid to coordinates specified relative to the geoid can be done using down-loaded software from the National Imagery and Mapping Agency (NIMA, http://164.214.2.59/GandG/wgs-84/geos.html). First of all such software has to include a representation of the geoid. The software available from NIMA is based on a geoid of resolution 0.25 degrees. The map in figure 1 shows the deviations between the EGM96 geoid and the WGS84 ellipsoid.

It may be worth stressing that representing an equipotential surface, rather than the matter distribution itself, the EGM96 geoid is much less structured than

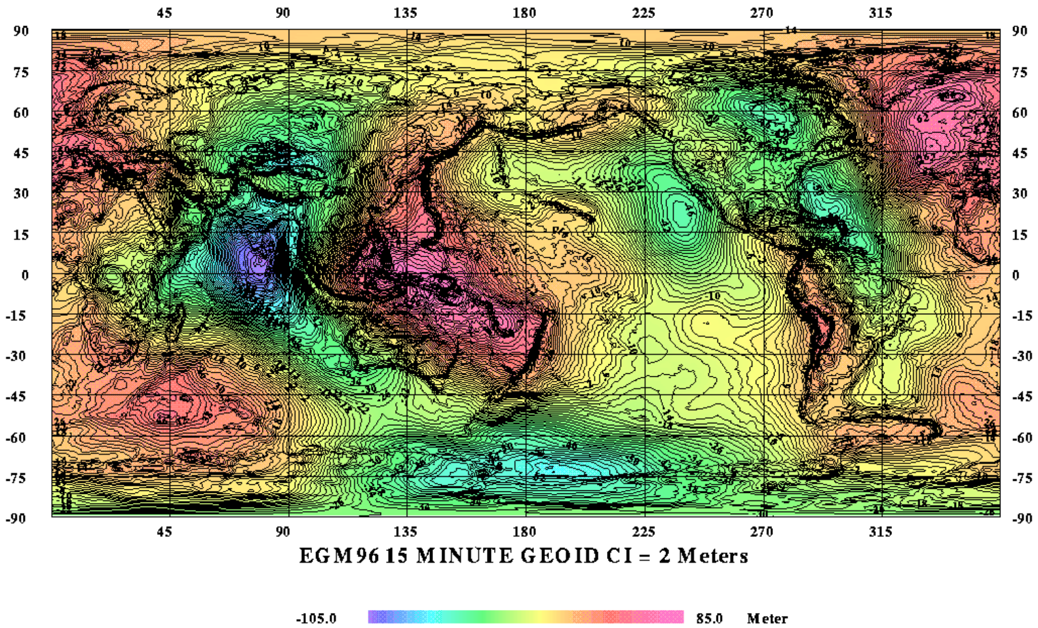

Figure 1: EGM96 geoid relative to WGS84 ellipsoid. From NIMA.

is the Earth surface; the resolution of the geoid used need not match that of the model orography.

Geopotential heights and HIRLAM.

In the HIRLAM model the vertical coordinate is pressure (or rather a simple function of pressure), not height. However, if one assumes the atmosphere is hydrostatic (or nearly so, which is generally a fine approximation), a relation between (geometric) height and pressure is established:

$$\delta p = -g\rho\delta z. \tag{1}$$

Here g is the net acceleration due to gravity and non inertial forces acting on a body at rest with respect to the surface of the earth.

Combining with an equation of state, $p = \rho RT$, we get,

$$RT\delta \ln p = -g\delta z, \tag{2}$$

which could be used to derive geometric heights from HIRLAM data.

This relationship is never used in the model, however, instead one uses *geopotential height*, here named h, which in the model is derived using

$$RT\delta \ln p = -g_o\delta h, \tag{3}$$

for the increment, while the model geopotential height itself is defined as,

$$h_H = h_{Hs} + \frac{1}{g_0}\int_p^{p_s} RT\delta \ln p, \tag{4}$$

with subscript H meaning HIRLAM and s surface. $g_0 = 9.80665\,\mathrm{m/s^2}$ is a value decided upon by the WMO and used by all met. offices.

(Indeed the variation of g with position is neglected in the NWP models, which is acceptable as long as it is done consistently, as the effect is very small compared to other short comings of the model. One should just remember that what the models know is the atmospheric properties as a function of pressure, *not* as a function of the true height, even though one sometimes speak about heights.)

From the above we see,

$$h_H(z) = h_{Hs} + \int_{z_{Hs}}^{z} \frac{g}{g_0}\, \mathrm{d}z, \tag{5}$$

where h_{Hs} is the geopotential surface height in the HIRLAM model corresponding to the geometric height of the HIRLAM surface, z_{Hs}.

The above definition (5) of the geopotential height is HIRLAM (or NWP model?) specific. The textbook definition of the geopotential height is (see e.g [2] or [6]) ,

$$h = \frac{1}{g_0} \int_0^z g\, \mathrm{d}z. \tag{6}$$

The definitions 5 and 6 are identical if h_{Hs} in the HIRLAM model is derived following 6. Unfortunately for the GPS $\rightarrow$ HIRLAM data conversion that is *not* the case.

The HIRLAM orography is specified via the so called *climate* files. In those the orography is given in terms of the HIRLAM geopotentials of the surface grid-points, which are deduced from geometric heights found in some data base containing Earth data. Once the geometric height of a surface grid-point is determined from these data, the corresponding HIRLAM surface geopotential is calculated as (Sattler [7]),

$$\Phi_{Hs} = z_s g_H \;\Rightarrow\; h_{Hs} = z_s \frac{g_H}{g_0}. \tag{7}$$

The value used for g_H in generation of the HIRLAM climate files is 9.81 m/s^2. Thus, the surface heights being used in HIRLAM are *not* geopotential heights; instead they are geometric heights (offset by a factor $g_H/g_0 = 1.0003416$, which over 5 vertical kilometers makes for a ≈ 1.7 m difference; a forgivable amount).

Hence, using the HIRLAM geopotential height definition the two bits $0 \rightarrow z_{Hs}$ and $z_{Hs} \rightarrow z$ transform differently. To make a calculation of h, which is proper in a HIRLAM sense, requires knowledge of z_{Hs} as seen by HIRLAM. One therefore has either to do the transformation inside the HIRLAM system, or extract the geopotentials from the climate files and use those data if doing the conversion prior to running the HIRLAM OI analysis. If doing it outside HIRLAM, one should remember that the conversion will be model specific, as changing the grid-size or structure calls for a new orography.

A third option is to simply neglect the effect of the differences in the geopotential height definitions. That is the only way facilitating a general derivation of the geopotential heights, for example if done by the GPS data vendor, prior to delivery of the profiles to the met. community. Further down we analyse the error of doing so, but first we need expressions for calculation the geopotential height in practice.

An analytical expression for geopotential height.

The acceleration g varies with position. An approximate expression for the value of g at the geoid surface as function of latitude can be found in Handbook of Chemistry and Physics [4],

$$g_s \approx g_e(1 + a_1 \sin^2\theta + a_2 \sin^2 2\theta), \tag{8}$$

where θ is the latitude, and $g_e = 9.780356\mathrm{m/s}^2$, $a_1 = 5.2885\ 10^{-3}$, and $a_2 = -5.9\ 10^{-6}$.

For the variation of g with height we may use,

$$g \approx g_s \left(\frac{R_s}{R_s + z} \right)^2 , \tag{9}$$

where R_s is the distance to the center of the earth from that point of the geoid surface. (For the sceptical mind a demonstration of the applicability of equation 9 is included in a forthcoming note on derivation of zenith total delays from meteorological data.) For R_s we use,

$$R_s \approx \frac{R_e}{\sqrt{(R_e/R_p)^2 \sin^2\theta + \cos^2\theta}}, \tag{10}$$

where the average equatorial radius is $R_e \approx 6378.1\mathrm{km}$ and the average pole radius is $R_p \approx R_e - 21.5\mathrm{km}$. (The numbers used are a compromise between various results listed in Handbook of Chemistry and Physics [4].)

Adding up we have the following expression for the (textbook) geopotential height,

$$h = \frac{g_s}{g_0} \int_0^z \left(\frac{R_s}{R_s + z} \right)^2 \mathrm{d}z = \frac{g_s}{g_0} \frac{z}{1 + z/R_s}, \tag{11}$$

while for the increment $z_1 \to z_2$ we get,

$$h_2 - h_1 = \frac{g_s}{g_0} \frac{z_2 - z_1}{1 + (z_2 + z_1)/R_s + z_1 z_2 / R_s^2}. \tag{12}$$

Figures 2 and 3 show the difference between the geometric height and the geopotential height, derived using equation 11, as function of geometric height at three different latitudes. Shown (in red) is also the similar difference derived using tabular data for the US standard atmosphere, which is derived for $\theta = 45$ degrees (table data from [4]). The fine resemblance indicates that relation 11 is sufficiently accurate for our purposes.

The offset between textbook and HIRLAM geopotential heights.

The offset between the "true" (i.e. textbook) geopotential height of the surface versus the HIRLAM geopotential height of the surface is given by,

$$\Delta h \equiv h_{Hs} - h = z_s \left(\frac{g_H}{g_0} - \frac{g_s}{g_0} \frac{1}{1 + z_s/R_s} \right). \tag{13}$$

Δh for surface heights up to 5 km and for three different latitudes is shown in figure 4.

Nielsen & Amstrup [5] provide obs-verification results for the HIRLAM model analyses against radiosonde data. One example, covering the month of September, 1999, is shown in figure 5 for easy reference. Further examples may be found in their figures 8-10 and in older reports, the figure included here is typical, however. The bias of the model geopotential height is of the order a few meters at pressures above 300 hPa (about 9 km), with a fast increase further up, whereas the rms values increase steadily from about 5 meters at 1000 hPa to about 13 m at 300 hPa, with a slightly fast increase further up, to about 28 m at 150 hPa (about 13.5 km).

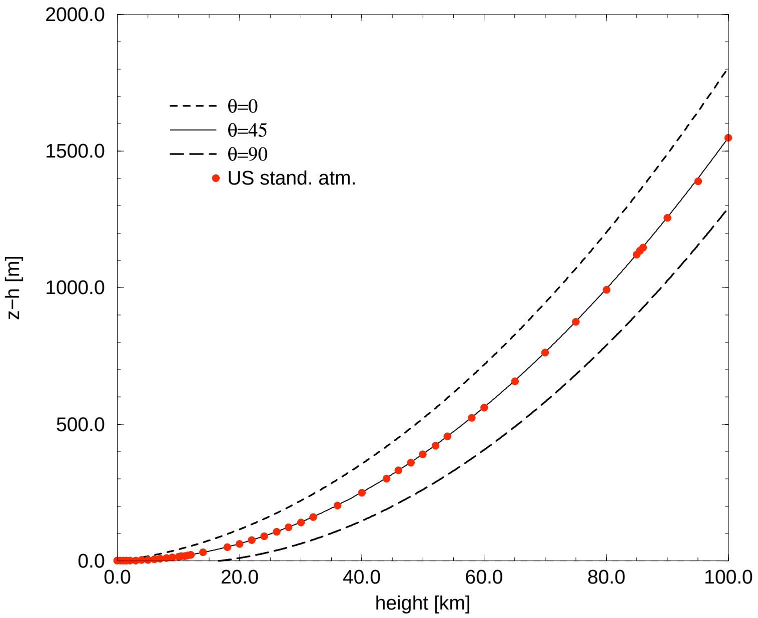

Figure 2: Geometric minus geopotential height derived using equation 11 and compared with US standard atmosphere data. See text for details

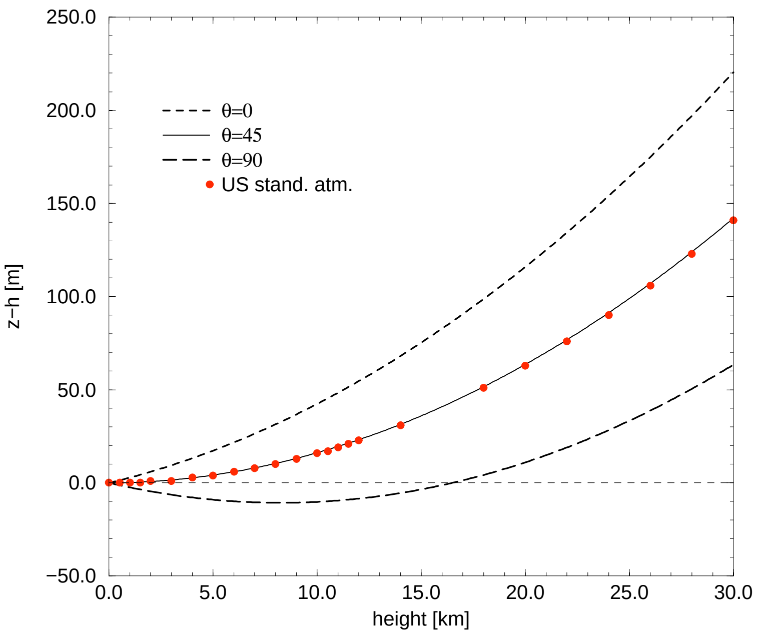

Figure 3: Enlargement of part of figure 2

Though this type of data are not comparable one to one with the geopotential surface height offsets considered in this section, they do give an idea about the precision with which HIRLAM is able to handle heights (assuming the errors in the radiosonde geopotential heights are not a dominant source of error).

Based on this comparison we conclude that the offsets shown in figure 4 are large enough that we ought to get rid of them, in order to maintain a level of precision for the heights of the profile data higher than that of the model itself, independent of geographical position.

On the other hand, the offsets are in-significant over the sea and low terrain

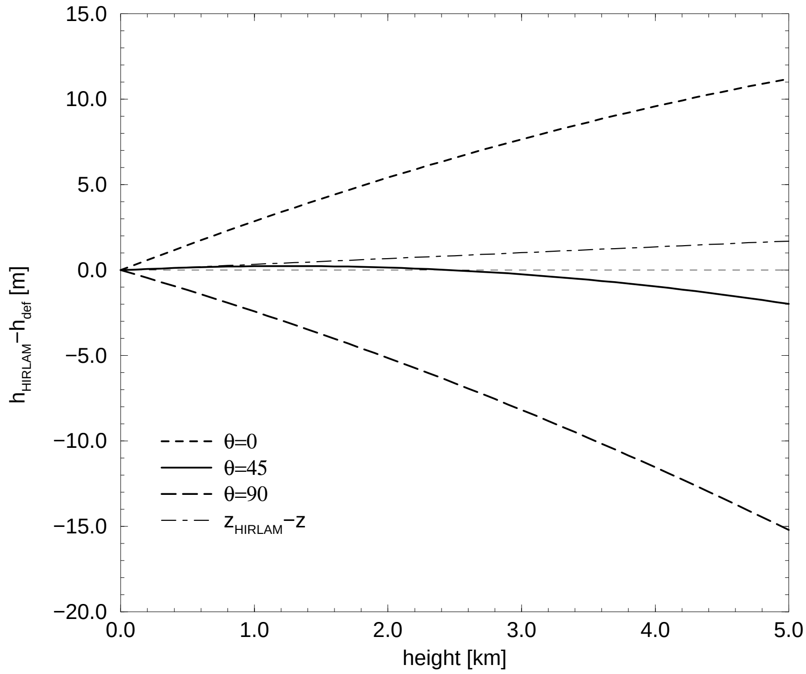

Figure 4: Difference between HIRLAM model geopotential surface height and true geopotential surface height as function of geometric surface surface height, for three different latitudes.

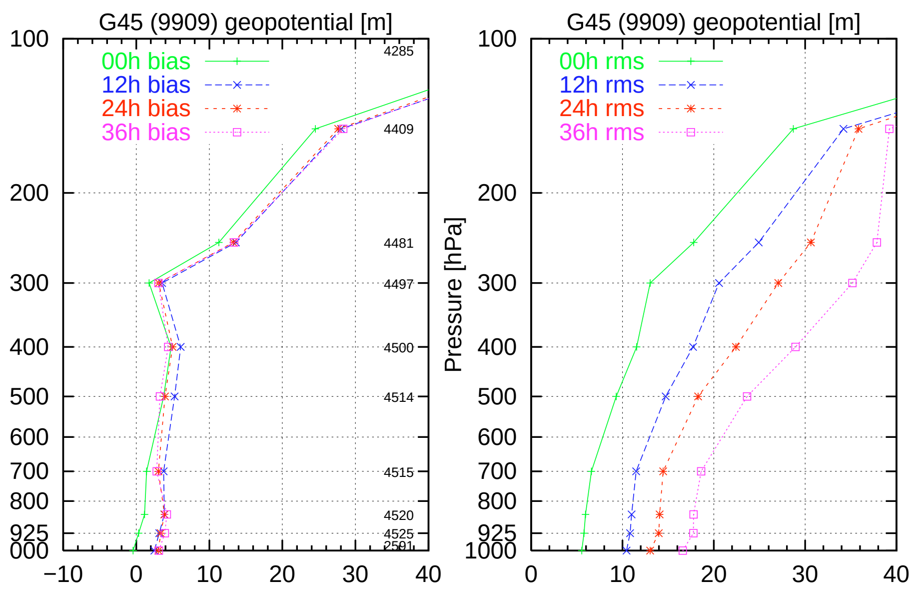

Figure 5: Obs-verification of HIRLAM geopotential heights against radiosonde geopotential height. From Nielsen & Amstrup [5].

compared to the precision of HIRLAM, regions which cover a large fraction of the earth as well as of the operational HIRLAM model regions. And the offsets are small compared to the error made in not making any conversion of geometric to geopotential height at all, chiefly figures 2 and 3. We conclude, that if, for various practical reasons, it is too cumbersome to make a proper correction – incorporating the HIRLAM offsets, we should use an equation like 11 to convert the geometric heights to geopotential heights, much rather than using no conversion at all.

Having realised the existence of an offset between HIRLAM geopotential heights and true geopotential heights it requires some pondering to assure oneself that this does not have any negative effects within the current HIRLAM setup. That is beyond the scope of this note however.

Clearly, there are some benefits from the HIRLAM surface being expressed in terms of geometric heights. For example the height of surface stations may be easily compared with the height of the HIRLAM surface, without any g-model dependent integration.

Neglecting the variation of g_s and R_s with latitude.

When given by the equations 11, 8, and 10 the geopotential height is a function of geometric height, latitude, and a set of empirically determined constants. Sometimes the dependence on latitude is disregarded by some, thus determining the geopotential height as $h = z/(1 + z/\overline{R})$, with $\overline{R}$ being some value for the average radius of the Earth.

Figure 6 shows the impact of doing so separately for g_s and R_s. In the left figure h was derived using $g_s = g_0$ in equation 11 for the geopotential height, while for the right figure h was found using $R_s = R_s(\theta = 45)$ in equation 11. In both cases the reference geopotential height, named h_{def} on the figure, was derived using equation 11 without any further assumptions.

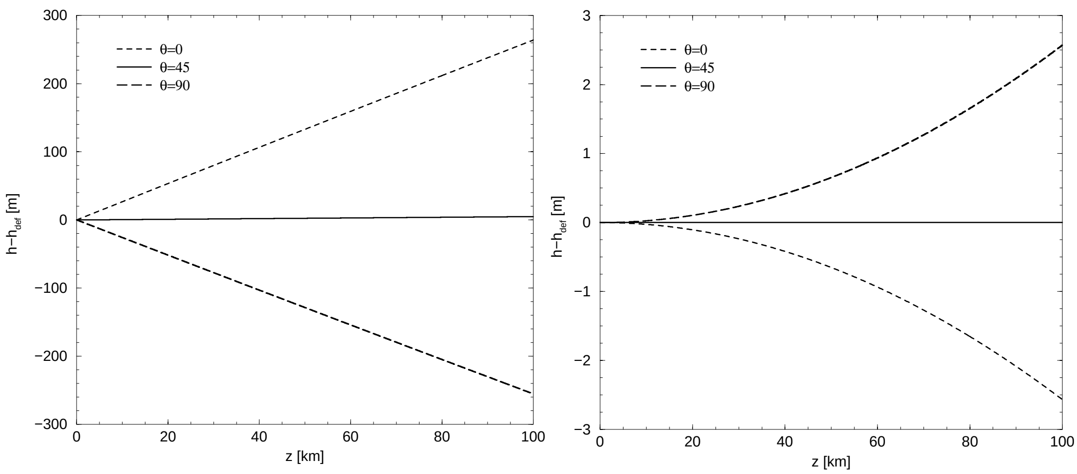

Figure 6: Ignoring the variation of g_s (left) and R_s (right) with latitude. Notice the different ordinate scales

Clearly the major part of the variation with latitude seen in figures 2 and 3 is due to the variation of the surface acceleration term g_s. The effect of ignoring the variation of R_s is much smaller, smaller than the offset between the HIRLAM and textbook geopotential heights discussed in the previous section.

Conclusion: The Solution(s).

If we neglect the differences between the HIRLAM surface heights and the corresponding proper geopotential heights we may calculate the geopotential height using 11 without any reference to HIRLAM model specific data. The errors from ignoring the height offsets are small over shallow terrain, but can be significant over mountainous terrain, up to about 15 meters as envisaged by figure 4.

If we decide to make a proper conversion of z to HIRLAM geopotential height, h_H, we may do it as,

$$h_H = h_{Hs} + \frac{g_s}{g_0} \frac{z - z_{Hs}}{1 + (z + z_{Hs})/R_s + z_{Hs}/R_s^2}, \tag{14}$$

where g_s is given by 8, R_s is given by 10, and $z_{Hs} = \Phi_{Hs}/g_H$, with Φ_{Hs} being the HIRLAM model surface geopotential at the specific location, found by interpolation in the orography data for the HIRLAM model in question.

Using any of the two approaches it is important not to neglect the variation of the surface gravity, g_s, with latitude. One may use $\overline{R_s}$ as a substitute for $R_s(\theta)$. However, both functionals (equations 8 and 10) are very easily handled by the computer and do not depend on NWP model parameters.

In an experiment conducted by Amstrup & Mogensen [1] a clear improvement of the fit between GPS profiles, in the form of pressure versus height, and ECMWF NWP model profiles was found when including the geometric to geopotential height conversion in a form based on equation 11.

Further about the GPS atmospheric profile data-types and their assimilation into NWP models.

Very often scientific measurement data need to be processed to various degree before being comparable to model variables or products. In general it is from a theoretical viewpoint always beneficial to utilise the data in the most "raw" form possible for the model in question, if one does not have access to another, superior model. In operational meteorology this aspect have to be balanced against other requirements, such as timeliness and impact.

The GPS atmospheric profile data are (or will become) available in three forms of potential interest to NWP modeling, namely

1 bending angle,

2 refractivity,

3 pressure, temperature, and humidity.

as functions of geometric height relative to the WGS84 ellipsoid.

All three may in principle be assimilated using a variational data assimilation system, whereas only the latter can be utilized by the current HIRLAM optimal interpolation system.

Of these data types the bending angles are the least processed. The GPS data vendors derive the refractivities from the bending angles based on assumptions about the symmetry of the problem, the (local) shape of the Earth, the horisontal stratification of the atmosphere, and a few other other things. Some of the assumptions may be relaxed if assimilating the bending angles directly into a NWP model using variational data assimilation. For example the inhomogeneities associated with the fronts of low pressure systems can be included in the meteorological analysis and hardly by the GPS data providers.

Assimilation of refractivities rather than bending angles is more straight forward and less time consuming, not requiring any extensive horisontal integrations of properties related to the model field variables. Until tests demonstrate the NWP benefits of using the bending angles directly it appears reasonable to focus on assimilation of atmospheric refractivities.

Conversion of the refractivity profile, $N(z)$, to a profile, (p, T, q), of pressure, temperature, and density requires further assumptions. In the neutral, dry atmosphere the refractivity is a function of density only. One may therefore determine $p(z)$ and $T(z)$ using the hydrostatic equation, an equation of state, and a fix-point specifying either p or T at a certain height high up in the neutral atmosphere, (e.g. Leroy [3]). In the wet atmosphere the refractivity becomes a function also of humidity, and it takes further, less solid, assumptions to continue the transformation towards the surface. This is of importance typically below 5 km (with some scatter and a general increase towards the tropics).

It would appear convenient to assimilate $T(p)$ to circumvent the problems encountered in calculation of h when assimilating $h(p)$. However, that is not possible in the HIRLAM OI system. It will be feasible in 3&4DVar data assimilation system under development for HIRLAM, but due to the large variations in the humidity field with position and time it is much safer, and probably much better, to assimilate refractivities directly, rather than convert them to pressure, temperature, humidity based on assumptions prior to assimilation.

An observational operator for geometric height.

Finally we notice that in a variational data assimilation system an observational operator can be written not only for the the refractivity, but also for the geometric height, as shown below. This is not necessarily the way in which GPS profile data will be assimilated in variational data assimilation systems in the future, many aspects have to be considered before choosing the optimal approach. But it is clear that it would be beneficial to the meteorological community if the providers of GPS profile data included a conversion from WGS84 to geoid heights to their products, as it is a problem about which the GPS community possess much more expertise than the meteorologists.

Having access to the NWP model field we may integrate the left-hand side of the hydrostatic equation (2) numerically,

$$\int_{p_{i-1/2}}^{p_s} RT\delta \ln p \approx \sum_{j=N}^{j=i} R_j T_j \ln\left(\frac{p_{j+1/2}}{p_{j-1/2}}\right) \equiv RTP_i, \qquad (15)$$

assuming the model grid cells are numbered $i = 1, \ldots, N$ in the vertical, with 1 being at the top, and denoting the corresponding cell boundaries by $i - 1/2$ and $i + 1/2$, and R_j being the proper gas-constant of the atmosphere in that cell, taking into account the humidity of cell j.

Based on the approximation for $g(z)$ used previously in this note we end up with,

$$z_{i-1/2} = z_{Hs} + \frac{R_{Hs} RTP_i}{R_{Hs} g_{Hs} - RTP_i}. \qquad (16)$$

Here g_{Hs} is the surface acceleration at the (HIRLAM) model surface deduced using equation 8 and $R_{Hs} = R_s + z_{Hs}$, with z_{Hs} being the geometric height of the model surface, available from the model orography, and R_s from equation 10. $z(p)$ or $p(z)$ may be found at intermediate levels by interpolation.

In a forthcoming paper we discuss the problems of calculating zenith delays of radio waves from NWP model data. That will include a discussion of the precision of various ways in which to relate in practice the pressure to the geometric height, both within in the model atmosphere and above.

Acknowledgments.

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