AN 22B-08: RETRIEVAL OF WATER VAPOR PROFILES FROM ATMOSPHERIC RADIO-OCCULTATIONS.

by

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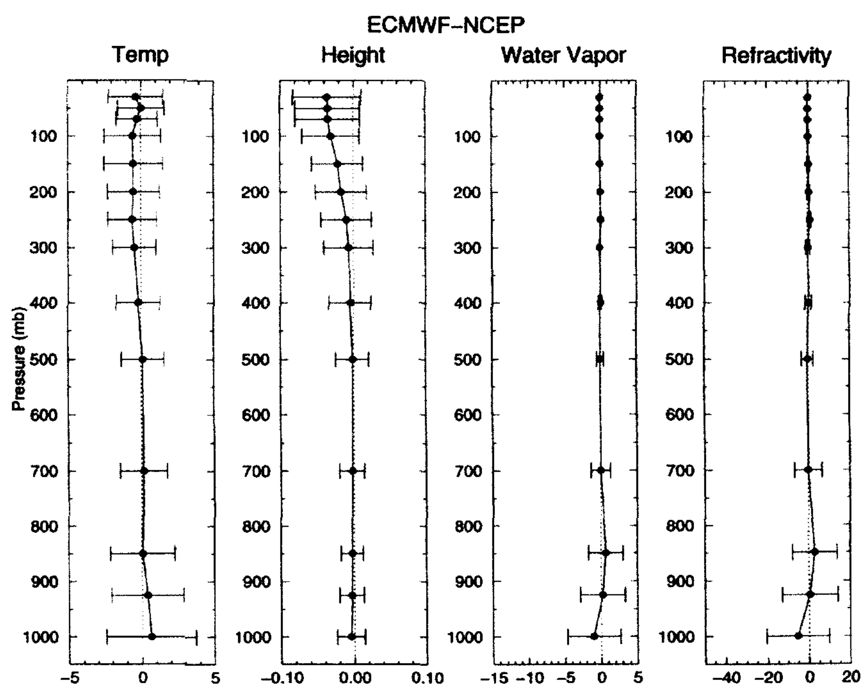
Abstract: Atmospheric radio-occultations provide high-resolution vertical profiles of atmospheric refractivity. Using the GPS frequencies for the occultations allows extraction of atmospheric state variables from areas within cloudy regions. The vertical resolution is ideal to detect small water vapor structures. Present retrievals of water vapor still rely heavily on the use of ancillary data like ECMWF or NCEP. This can be a conflict when the ancillary data and occultations disagree. We illustrate a novel method to extract water vapor with high vertical resolution, using the refractivity profiles without ancillary data. We also discuss the estimated accuracies and sources of error.

Introduction:

Water vapor is the dominant green-house gas in the atmosphere. It remains difficult to measure with remote sensing techniques, and Global Circulation models show significant discrepancies with the data.

GPS radio occultations provides valuable remote sensing data that can improve our understanding of the global water vapor distribution. Standard retrieval approaches use temperature profiles derived from global weather analyses to infer water vapor from the GPS measurements of refractivity versus height. In a significant fraction of the retrievals, errors in the weather analyses are the dominant source of water vapor retrieval error for GPS occultations. This poster explores a new approach to estimating water vapor that does not rely on a weather analysis.

Figure 1: Comparison between NCEP and ECMWF:



O'Sullivan, D.B., B.M. Herman, D. Feng, D.E. Flittner, and D.M. Ward, 2000. Retrieval of water vapor profiles from GPS/MET radio occultations. Bull. Amer. Meteor. Soc., May, 2000.

Figure 2: Precision of a previously reported model-independent approach: (requiring ancillary data at ground level.)

O'Sullivan, et al. Bull. Amer. Meteor. Soc., May, 2000.

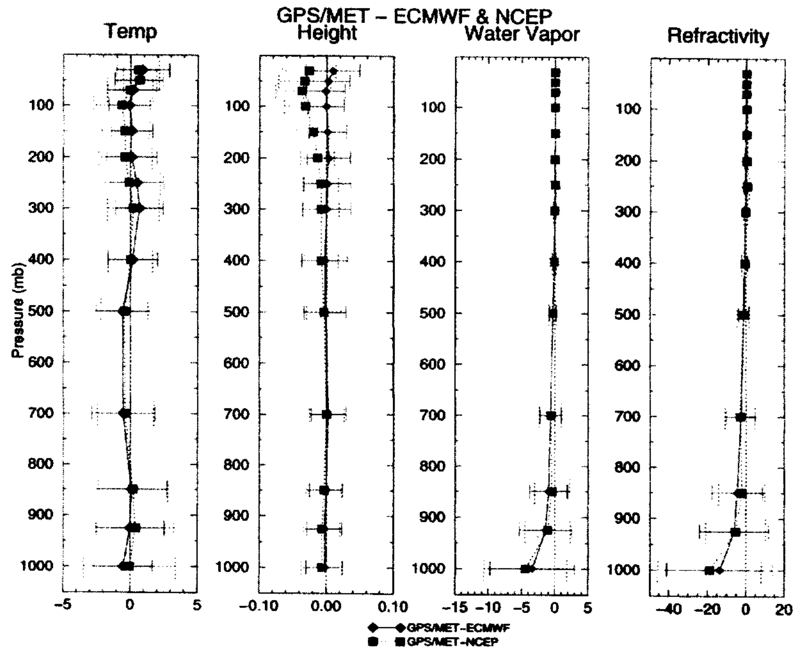


Fig 3: Current uncertainty in our knowledge of specific humidity:

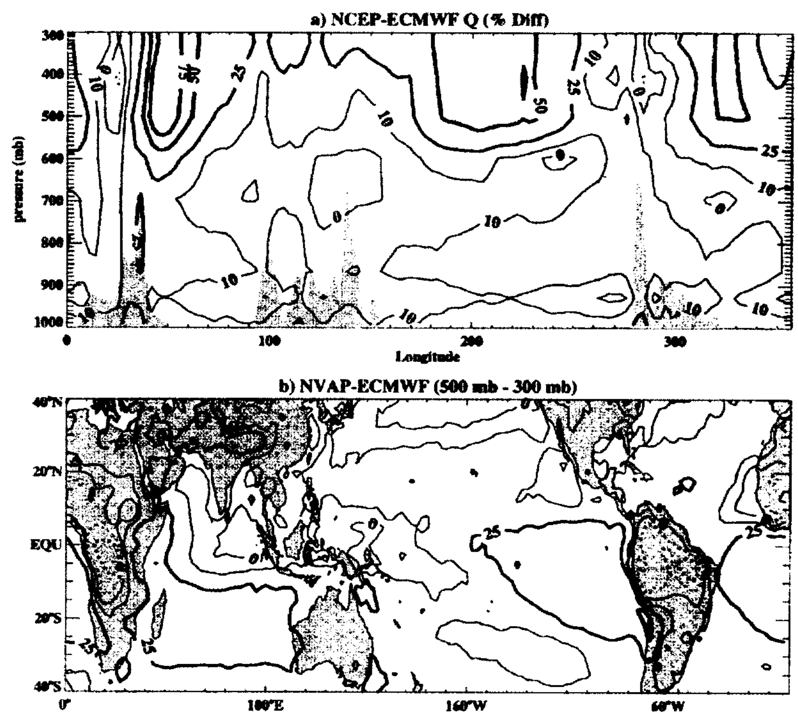


FIG. 1. Humidity differences between (a) the ECMWF and NECP–NCAR reanalysis averaged across 5°S–5°N and (b) the ECMWF reanalysis and NVAP retrievals from 500 to 300 mb.

Fasullo, J., and D.-Z. Sun , 2001: Radiative sensitivies to tropical water vapor under all-sky conditions. J. Climate, 2798-2807.

Objectives:

- Capturing small-scale water vapor structures that are undetected by analyses or other sensing techniques.
- Obtaining water vapor retrievals from radio-occultations when differences between model and measurements occur.

Method:

The refractivity measured above a given height z_0 is used to model density locally ($1-2$ km intervals along the vertical) under the constraints of hydrostatic balance, constant lapse rate, and constant specific humidity q.

The difference between the local extrapolation of this model and the measured refractivity is assumed to be caused mainly by a Δq. This jump in q is then inferred from the difference between extrapolation and measurement. This is done in three steps:

1. Atmospheric refractivity relates to density by:

$$N = k_1 \frac{p}{T} + k_2 \frac{e}{T} + k_3 \frac{e}{T^2} = R_d k_1 \left[1 + q \left(\frac{R_w}{R_d} - 1 \right) + \frac{k_2 R_w}{k_1 R_d} q + \frac{k_3 R_w}{k_1 R_d} \frac{q}{T} \right] \rho \quad (1)$$

T is temperature in Kelvins, p is total pressure in millibars, e is water vapor pressure in millibars, $k_1 = 77.6$ K/mbar, $k_2 = -12.8$ K/mbar, and $k_3 = 3.776 \times 10^5$ K^2/mbar. $R_d = R/M_d = 287$ is the gas constant for dry air, M_d is the molecular mass for dry air, $R_w = R/M_w = 462$ is the gas constant for water, M_w is the molecular mass for water vapor, ρ is the total density, $\rho_w = \rho \cdot q$ is the water vapor density.

Hydrostatic balance, $\partial_z p = -\rho g$, in a moist ideal gas,
$p = R_d \left[1 + (R_w/R_d - 1)q\right] \rho T$,

Constant lapse rate, $\partial_z T \equiv -\Gamma$, and constant specific humidity give:

$$\frac{\rho(z)}{\rho(z_0)} = \left[1 - \frac{\Gamma}{T(z_0)}(z - z_0)\right]^{-B} \tag{2}$$

with $B = 1 - \frac{gM_d}{\Gamma R}$. For typical tropospheric values
$\Gamma(z - z_0)/T(z_0) < 8 * (1 \leftrightarrow 2)/250 = 0.03 - 0.06$, thus if a Taylor expansion is used:

$$log\left[\frac{\rho(z)}{\rho(z_0)}\right] = B\left[\frac{\Gamma(z - z_0)}{T(z_0)} + \frac{\Gamma^2(z - z_0)^2}{2!T^2(z_0)} + ...\right] + O(\delta) \tag{3}$$

The first term of this Taylor expansion corresponds to an exponential. The second is less than $1.5 - 3.2\%$ of the first if z_0 were taken at a distance of 1 or 2 km. In our local approach, z_0 is chosen at the nearest point to the extrapolation. The distance is thus typically 0.5 km and the maximum correction in the second term is 1% of the first or less. The values extrapolated in our fits showed typical refractivity differences of less than 0.5%. These corrections compare with current errors in refractivity estimates (different retrieval options differ by approximately 2%.)

The coefficients of equation (3) are obtained by least-squares fit of the data to the first term of the Taylor expansion:

$$log\left[\frac{\rho(z)}{\rho(z_0)}\right] = a_0 + a_1(z - z_0)$$

The independent term a_0 is used to partly represent the neglected terms. Higher order fits including the non-linear terms were also used but they were observed to produce unphysically large values. This may be caused by errors which get amplified non-linearly in the extrapolation. Non-linear approaches may need a different type of algorithm. Including them as a constant a_0 seems to work in preventing the amplification of such errors.

2. Extrapolate ρ down to the nearest lower level (z_{i+1}).

$$N(z_{i+1}) = N(z_i) + \Delta N|_{q=q_o} + \Delta N|_{z_{i+1}} =$$

$$= N(z_i) + [c(q,T)\Delta\rho + \rho\Delta c(q,T)]_{q=q_o} + \Delta N|_{z_{i+1}} \tag{4}$$

3. The difference with the observed $\Delta N|_{z_{i+1}}$ is assumed to be dominated by changes in Δq which were not included in equation (3). We assume that the total number of molecules per unit volume is conserved, thus a mole of water vapor is replaced by a mole of dry air. This prevents imposing the uppermost density scale height all the way down to the bottom of the atmosphere.

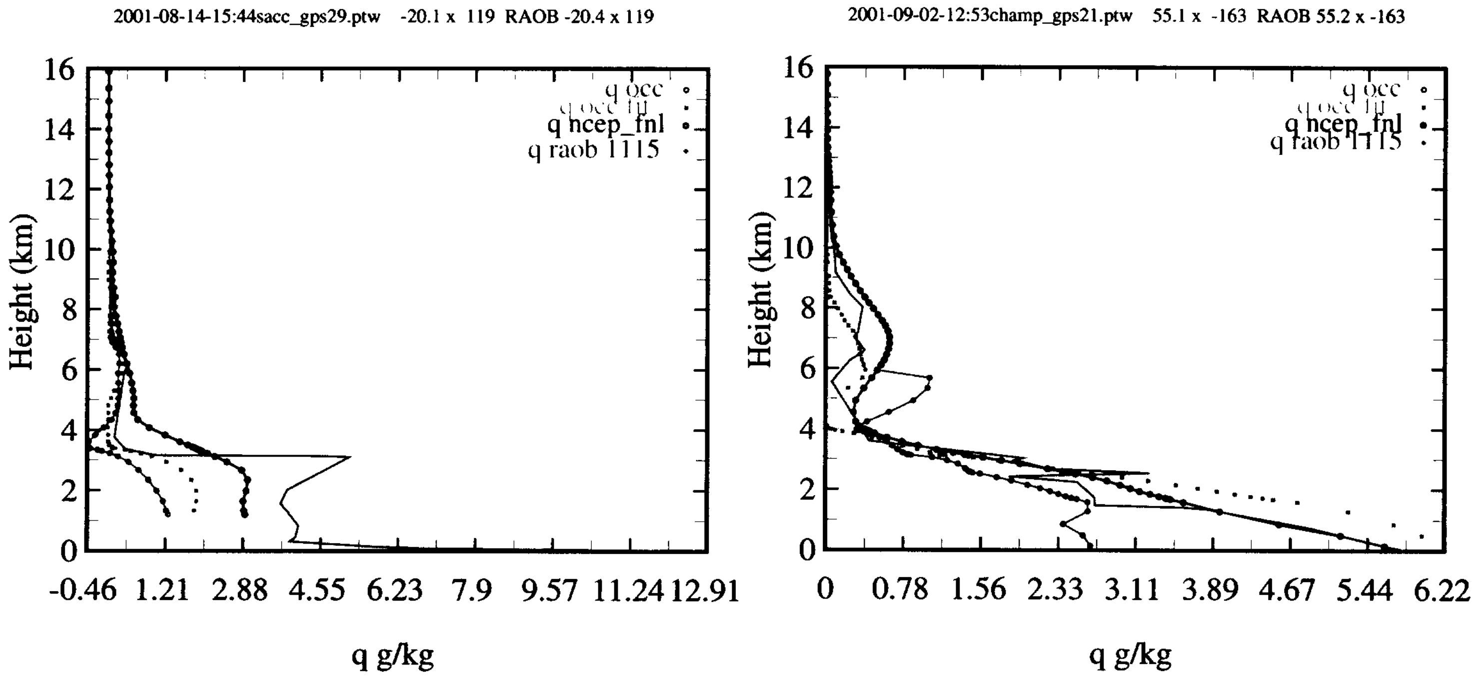
$$\Delta N|_{z_{i+1}} = R_d k_1 \left[\left(\frac{R_w}{R_d} - 1\right) + \frac{k_2 R_w}{k_1 R_d} + \frac{k_3 R_w}{k_1 R_d}\frac{1}{T}\right] \rho\Delta q + \tag{5}$$

$$+ R_d k_1 \left[\left(\frac{R_w}{R_d} - 1\right) + \frac{k_2 R_w}{k_1 R_d} + \frac{k_3 R_w}{k_1 R_d}\frac{1}{T}\right] \Delta\rho|_{z_{i+1}} q$$

Because temperature only appears in one of the terms within the brackets, this approach does not require an accurate temperature retrieval. Thus, model temperature can be used even in cases where its refractivity differs significantly from the occultation values.

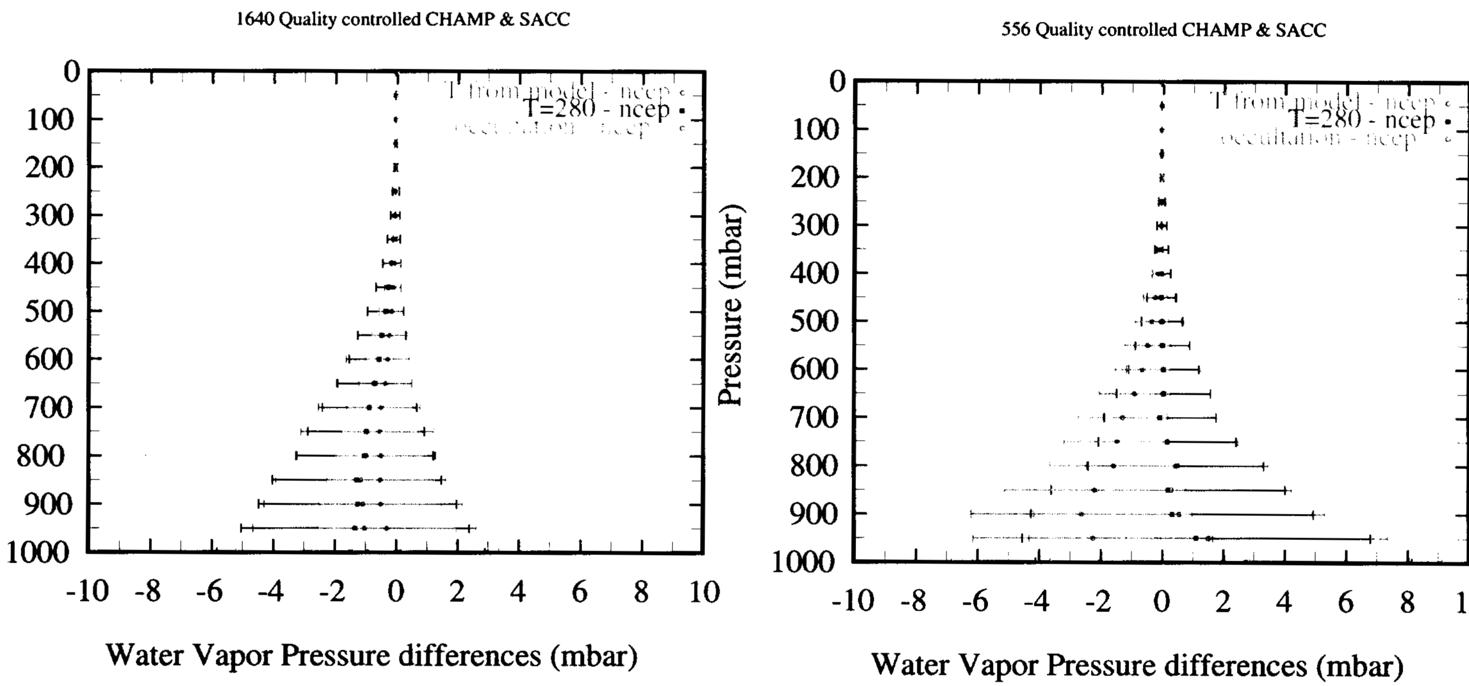
Results:

Comparison with the fine resolution of radiosondes:



Figures 4 & 5: Two nearby radiosonde soundings (violet) are compared with a standard radio-occultation retrieval (green) and the method described here (blue). The new method is able to capture thin water vapor structures that the models and the current radio-occultation processing misses in Figure 4. Figure 5 shows an artificial structure occuring in the current processing because water vapor is retreived only “below” 250 K. The water vapor structure near 8 km is captured this time by the model, radiosonde, and our fit-based occultation retrieval but incorrectly by the current processing technique.

Comparisons with the current processing technique:

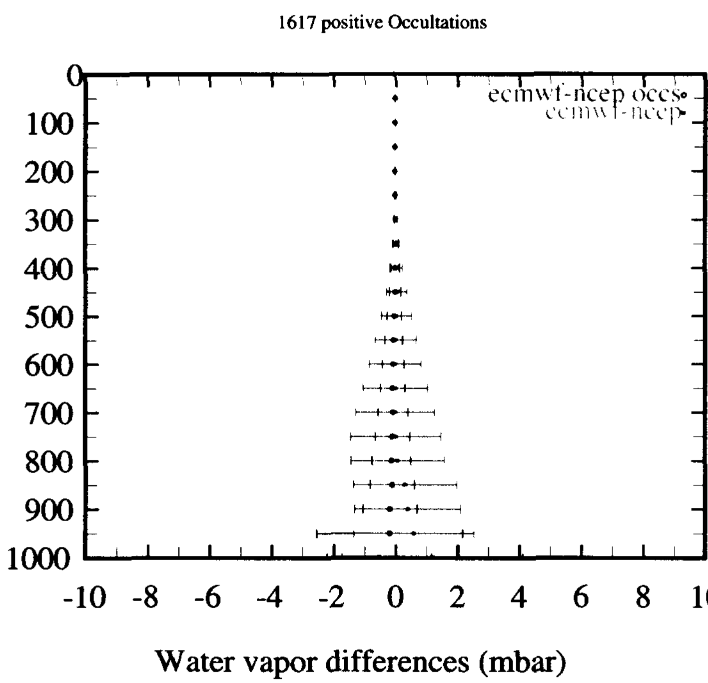


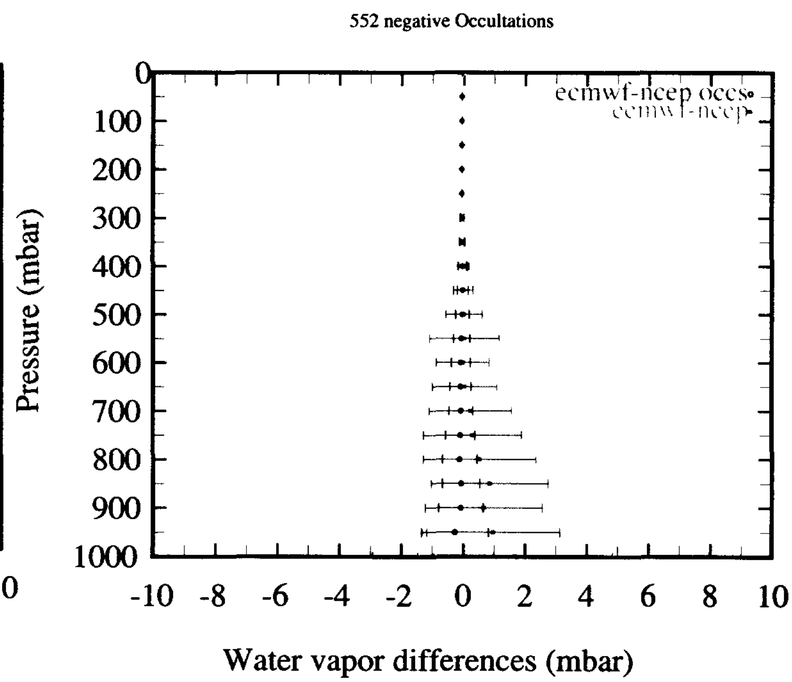
Figures 6 & 7: 4000 occultations from SAC-C and CHAMP were chosen. Out of those, the ones where the refractivity differed from NCEP by less than 10% were kept to make a comparison of water vapor retrievals. Of these about 25% resulted in negative water vapor pressure values at some heights with the standard processing. The mean and standard deviation of the differences with NCEP are shown in both figures as a function of height.

Figure 6 (on the left) shows the cases where water vapor pressure remained positive. Figure 7 corresponds to the cases where some values became negative.

Water vapor from occultations without ancillary data.

Comparisons with ECMWF:





Figures 8 & 9: The occultations from figures 6 & 7 were retrieved using ECMWF and a similar comparison was repeated. Several occultations that could be retrieved using NCEP, did not work when using ECMWF. The mean and standard deviation of the differences between ECMWF and NCEP are shown in both figures as well as the differences in the retrieved occultations using each model as ancillary data.

Figure 8 (on the left) shows the results for the occultations in Figure 6, and Figure 9 corresponds to the occultations in figure 7.

Conclusions:

Simple physical principles may be used to estimate water vapor in radio occultation soundings of the atmosphere.

One expects these preliminary results to improve with the introduction of convective adjustment parametrizations, thermodynamic constraints (like the Clausius Clapeyron law), nonlinear terms, or improved mathematical algorithms (for example iterative approaches), but the current situation already compares favorably with related previous techniques, and is reasonably close to the standard retrievals which rely on weather analyses.

- Figure 7 show that the statistics of the new method are comparable to the current radio-occultation approach when the water vapor pressure is forced negative due to presumed errors in the analyses (this occurs in about 25% of the occultations.)
- The new method may provide valuable qualitative information on thin water vapor structures in the upper troposphere (T ¡ 250 K), where their role is crucial for understanding tropospheric-stratospheric exchange and heterogeneous chemistry.
- Significant accuracy improvement over the previous work of O'Sullivan et al. 2000 is suggested by our statistical analysis.

Acknowledgements:

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