



Differential absorption radar techniques: surface pressure

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Abstract. Two radar pulses sent at different frequencies near the 60 GHz O₂ absorption band can be used to determine surface pressure by measuring the differential absorption on and off the band. Results of inverting synthetic data assuming an airborne radar are presented. The analysis includes the effects of temperature, water vapor, and hydrometeors, as well as particle size distributions and surface backscatter uncertainties. Results show that an airborne radar (with sensitivity of -20 and 0.05 dBZ speckle and relative calibration uncertainties) can estimate surface pressure with a precision of ~ 1.0 hPa and accuracy better than 1.0 hPa for clear-sky and cloudy conditions and better than 3.5 hPa for precipitating conditions. Generally, accuracy would be around 0.5 and 2 hPa for non-precipitating and precipitating conditions, respectively.

1 Introduction

Surface pressure is an essential variable in atmospheric dynamics and numerical weather forecasting. Historically, its spatial distribution has been used to reveal weather system patterns such as depressions, anticyclones, troughs, ridges, and blocks. However, despite its importance, it is not yet available from remote sensing measurements, and hence there are large gaps in the measured surface pressure coverage, particularly over oceans.

Over the last decades, several techniques to remotely measure surface pressure have been proposed. All of them are based upon comparing radiation backscatter in an O₂ band with the radiation in a nearby atmospheric window. In other words, one measurement needs to be sufficiently far into the band (online) to be notably affected by changes in the O₂ total mass, while the other needs to be on the wing of the band

(offline) and in consequence barely affected by O₂ absorption. The ratio of these measurements, or the differential absorption, is then a measure of the O₂ column abundance and since O₂ is a well-mixed gas, a proxy for surface pressure.

The basic idea was proposed by Hanel (1961) for the estimation of cloud top height from a satellite. The method was based on measuring the absorption of cloud-reflected sunlight in the $2\ \mu\text{m}$ CO₂ band. Yamamoto and Wark (1961) improved this method by recommending the $0.76\ \mu\text{m}$ O₂ A band instead, a region with stronger signal and minimal interference from other species. Promptly, several authors (Singer, 1968; Smith et al., 1972; Barton and Le Marshall, 1979; Korb and Weng, 1982) proposed to use the same band but with a laser as a light source instead of the Sun. This technique is known as differential absorption lidar (DiAL). Barton and Scott (1986) suggested a passive instrument following Yamamoto and Wark (1961) but focusing on the surface as a reflecting layer. However, due to the inability of visible radiation to penetrate clouds, these pressure measurements are restricted to clear-sky areas and above clouds elsewhere. Furthermore, the passive instrument is restricted to daytime measurements only.

Flower and Peckham (1978) proposed the use of a differential absorption radar (DAR) in the 60 GHz (5 mm) O₂ band, noting that at microwave frequencies the cloudy coverage limitation is greatly reduced. They investigated the use of up to six radar tones covering frequencies from ~ 25 to ~ 75 GHz. Such a wide spectral region was needed to estimate the total water vapor column as well as the dry surface pressure. Recently, Lin and Hu (2005) and Lawrence et al. (2011) investigated a radar system with only two tones between 50 and 55 GHz. In this paper we revisit the DAR concept. In Sect. 2, the physics of the radar echoes are discussed. Section 3 introduces a general model for computing

radar echoes for any scene type (clear-sky, cloudy, or precipitating). Simulated differential absorptions measurements are covered in Sect. 4 and results of synthetic retrievals are discussed in Sect. 5. Results show that this technique has the potential of achieving ~ 0.5 to 3.5 hPa (the latter for precipitating scenes) accuracy with realistically attainable airborne radar technology.

2 Theory

The return power measured by a monostatic radar which transmits a power P_T at wavelength λ can be simplified as

$$P_R(\lambda, s) = \frac{P_T(\lambda)G^2\lambda^2\Omega}{(4\pi)^2r^2}\Upsilon^2(\lambda, s)\eta(\lambda, s)\Delta r, \quad (1)$$

where G is the antenna gain, r is the range to the target, Ω is the two-way solid angle, Δr is the range resolution, $\eta(\lambda, s)$ represents the hydrometeors backscatter coefficients, and $\Upsilon^2(\lambda, s)$ is the two-way transmission along the slant path s given by

$$\Upsilon^2(\lambda, s) = \exp\left(-2\int_0^r [\sigma_{\text{gas}}(\lambda, s) + \sigma_{\text{Pext}}(\lambda, s)] ds\right), \quad (2)$$

where $\sigma_{\text{gas}}(\lambda, s)$ represents the gaseous absorption coefficient and $\sigma_{\text{Pext}}(\lambda, s)$ the particulate extinction (the sum of absorption and scattering) coefficient.

Equation (1) can be further simplified as

$$P_R(\lambda, s) = \frac{C(\lambda)\Upsilon^2(\lambda, s)\eta(\lambda, s)}{r^2}\Delta r, \quad (3)$$

where $C(\lambda) = P_T(\lambda)G^2\lambda^2\Omega/(4\pi)^2$ is the radar system parameter varying with the radar wavelength.

Assuming that the radar tones are chosen close to a strong absorption line, the wavelength dependence of $\sigma_{\text{Pext}}(\lambda, s)$ and $\eta(\lambda, s)$ is small relative to that of $\sigma_{\text{gas}}(\lambda, s)$ (see Fig. 1); the ratio of the return radar powers is given by

$$\frac{P_R(\lambda_1, s)}{P_R(\lambda_2, s)} = \frac{C(\lambda_1)\Upsilon^2(\lambda_1, s)}{C(\lambda_2)\Upsilon^2(\lambda_2, s)}, \quad (4)$$

where

$$\frac{\Upsilon^2(\lambda_1, s)}{\Upsilon^2(\lambda_2, s)} = \exp\left(-2\int_0^r [\sigma_{\text{gas}}(\lambda_1, s) - \sigma_{\text{gas}}(\lambda_2, s)] ds\right), \quad (5)$$

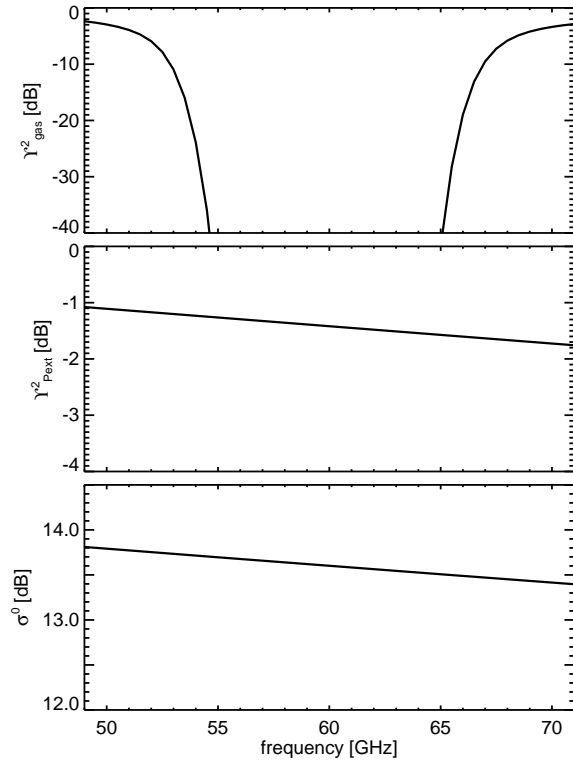


Figure 1. Typical atmospheric transmittance due to gases (top) and hydrometeors (middle) (Eq. 2) for a surface return journey (downward atmospheric pass, surface reflection, upward pass) for a nimbostratus cloud near the 60 GHz O_2 band region. (bottom) Ocean backscatter for a surface wind of 3 m s^{-1} and temperature of 28°C . Note that only the transmittance due to gases (top) show a significant frequency dependence.

which becomes

$$\frac{\Upsilon^2(\lambda_1, s)}{\Upsilon^2(\lambda_2, s)} = \exp\left(-2\int_0^r \rho(s) \sum_i v_i(s) [\kappa_i(\lambda_1, s) - \kappa_i(\lambda_2, s)] ds\right), \quad (6)$$

where $\rho(s)$ is the air density and the sum is over all the absorbers with monochromatic absorption coefficient $\kappa_i(\lambda, s)$ and volume mixing ratio $v_i(s)$.

Using the ideal gas law,

$$\frac{P_R(\lambda_1, s)}{P_R(\lambda_2, s)} = \frac{C(\lambda_1)}{C(\lambda_2)} \exp\left(-2\int_0^r \frac{p(s)}{RT(s)} \sum_i v_i(s) [\kappa_i(\lambda_1, s) - \kappa_i(\lambda_2, s)] ds\right), \quad (7)$$

where R is the gas constant, p is pressure, and T is temperature.

Furthermore, close to a strong absorption line, the monochromatic absorption coefficient for the rest of the absorbers (at two close enough wavelengths) are similar, leaving mostly the influence of the main absorber. For example, next to the 60 GHz O₂ absorption band, Eq. (7) can be simplified as

$$\frac{P_R(\lambda_1, s)}{P_R(\lambda_2, s)} = \frac{C(\lambda_1)}{C(\lambda_2)} \exp\left(-2 \int_0^r \frac{p(s)}{RT(s)} v_{O_2}(s) [\kappa_{O_2}(\lambda_1, s) - \kappa_{O_2}(\lambda_2, s)] ds\right), \quad (8)$$

where, since the O₂ mixing ratio is well known, the only unknowns remaining are pressure and temperature. Then, it follows that, assuming a temperature profile (e.g., from analysis fields), it should be possible to retrieve surface pressure from the backscattered return from the Earth's surface.

In this study a pulsed radar system will be simulated to explore the expected uncertainty characteristics of surface pressure retrievals based on the physics of Eq. (7). We consider a radar minimum detectable signal (sensitivity) of -20 dBZ and speckle and relative calibration uncertainties of 0.05 dBZ, with a vertical resolution of 500 m, and assume a sub-second integration time resulting in a sub-kilometer-scale horizontal resolution. These system parameters should be achievable from an airborne platform. We consider both instrument uncertainties and those associated with the assumptions necessary in the measurement inversion process.

3 Radar forward model

Simulated radar reflectivities were calculated computing the scattering properties of cloud and precipitation hydrometeors by means of Mie scattering theory, evaluating the gaseous absorption using the absorption coefficient calculations of the clear-sky forward model for the EOS Microwave Limb Sounder (MLS) (Read et al., 2006), estimating the single and multiple scattering by the hydrometeors using the fast time-dependent two-stream approximation described by Hogan and Battaglia (2008), and computing the ocean radar backscatter by a quasi-specular scattering model (Valenzuela, 1978; Brown, 1990; Li et al., 2005).

3.1 Optical constants

The dielectric properties of water and ice hydrometeors were taken from the parametrizations described by Liebe et al. (1991) and Hufford (1991), respectively. These parametrizations were developed using empirical fits to published experimental data and can be considered as an evolution of the commonly used Ray model (Ray, 1972).

3.2 Hydrometeors size distributions

3.2.1 Ice water content

We assume that all ice clouds can be described in terms of the McFarquhar and Heymsfield (1997) particle size distribution (PSD) parametrization derived from measurements during the Central Equatorial Pacific Experiment Campaign. This PSD characterizes the average properties of tropical ice crystal size distributions, dependent on temperature and ice water content (IWC). This PSD is commonly used in cloud retrieval algorithms including that of the EOS-Microwave Limb Sounder (MLS), ODIN Sub-mm Radiometer, and the Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES) (Wu, 2006; Eriksson et al., 2007; Millán et al., 2013).

3.2.2 Liquid water content

Measurements using a wide variety of techniques show that the mean liquid cloud drop radius varies from 2 to around 16 μm depending on the type of cloud (Howell, 1949; Squires et al., 1958; Fitzgerald and Spyers-Duran, 1973; Tsay and Jayaweera, 1984; King, 1993; Gerber, 1996; Yum, 2002). In this study, we model liquid clouds using a lognormal distribution with a 10 μm median radius and a 1.3 spread. The lognormal distribution is described by

$$n(r) = \frac{N_0}{\sqrt{2\pi}} \frac{1}{\log(\zeta)} \frac{1}{r} \exp\left(\frac{-(\log(r) - \log(r_m))^2}{2\log^2(\zeta)}\right), \quad (9)$$

where $n(r)$ is the number density of particles as a function of the radius r , N_0 is the total number of particles, r_m is the median particle radius of the size distribution, and ζ is the spread of the distribution where the standard deviation of $\log(r)$ is equal to $\log(\zeta)$.

3.2.3 Rain

Precipitating liquid was distributed according to the Abel and Boutle (2012) PSD. This distribution was derived from in situ aircraft measurements in a wide variety of precipitation from stratocumulus to heavy stratiform rain. This PSD is described by an exponential function with variable intercept and slope parameters which are functions of the rain water content.

3.2.4 Snow

Precipitating ice was modeled using the snow size distribution of Sekhon and Srivastava (1970), an exponential function derived from extensive field studies.

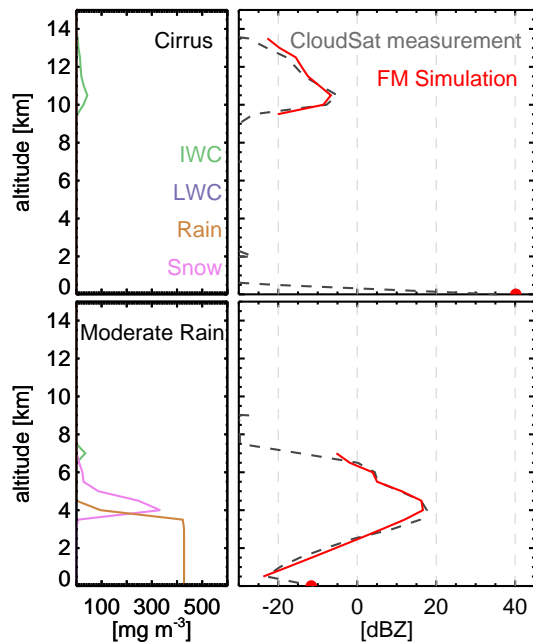


Figure 2. Comparisons between CloudSat measurements and forward model simulations. Forward model simulations are only shown for those altitudes with hydrometeors; the surface return is represented by a dot. For a detailed description see Sect. 3.6.

3.3 Gas absorption

The absorption coefficient with respect to volume mixing ratio, κ^i for the i th species, was computed using

$$\kappa^i = \kappa_{\text{LBL}}^i + \kappa_{\text{cont}}^i, \quad (10)$$

where κ_{LBL}^i is the line-by-line cross-section contribution described in Read et al. (2004, Chapter 11) and Read et al. (2006) using a Voigt lineshape with a Van Vleck–Huber prefactor (Huber and Vleck, 1966; Buehler et al., 2005) and where κ_{cont}^i is the continuum contribution described in Read et al. (2004, Chap. 12). Molecular line strengths and frequencies were taken from the HITRAN database (Rothman et al., 1998) and the JPL spectroscopy catalog (Pickett et al., 1998) in the same manner as the EOS MLS molecular line catalog (Read et al., 2006).

3.4 TDTS approximation

Using the scattering properties and the gaseous absorption previously computed, we use the publicly available code described by Hogan (2013), which follows the time-dependent two-stream (TDTS) approximation by Hogan and Battaglia (2008) to compute the time-dependent radar return. This model splits the photons into two categories: those that have only being affected by single scattering and those that have experienced wide-angle multiple scattering events. The time-dependent two-stream model has

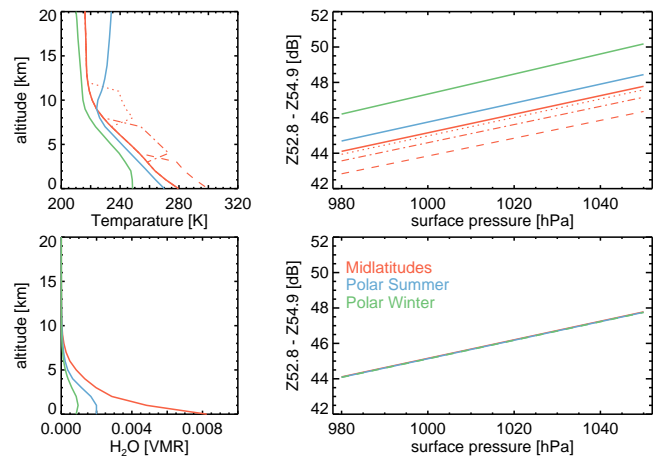


Figure 3. Simulated clear-sky relationships between surface pressure and surface radar returns. The top row shows the effect of varying the temperature profile while the bottom shows the effect of varying water vapor. Each color-coded point represents an adjustment of the entire pressure profile.

been shown to perform well in comparison with benchmark Monte Carlo simulations in most cloud scenarios of interest here (i.e., not deep convection) while being more computationally efficient (Battaglia et al., 2010).

3.5 Ocean radar backscatter

Ocean surface backscattering properties were computed with the quasi-specular scattering model for low incidence angles described by Valenzuela (1978), Brown (1990), and Li et al. (2005). This model has been used in the external calibration of CloudSat (Tanelli et al., 2008) and the Radar Aéroporté et Sol de Télédétection des Propriétés Nuageuses (RASTA) (Bouniol et al., 2008). Mean-square surface slopes were taken from the empirical relationship described by Wu (1990), using the microwave dielectric constants for seawater modeled by Klein and Swift (1977). The incidence angle was assumed to be zero (nadir), the sea surface temperature 28 °C, the surface wind 3 m s⁻¹, the Fresnel reflection coefficient correction factor 1 and zero salinity (which does not impact radar observables at around 60 GHz).

3.6 Forward model evaluation

A prerequisite for any synthetic retrievals discussion is a forward model evaluation. For this purpose, we use retrievals from CloudSat (Stephens et al., 2002) R04 algorithms as input to the forward model. The intent here is merely to demonstrate that our microphysical and radiative transfer models are consistent with those of the independent CloudSat retrieval algorithms. Here we use the 2B-GeoProf measurements as well as the liquid water content (LWC) and IWC profiles from the 2B-CWC-RO R04; the rain and snow profiles from the 2C-RAIN-PROFILE retrieval products; and the

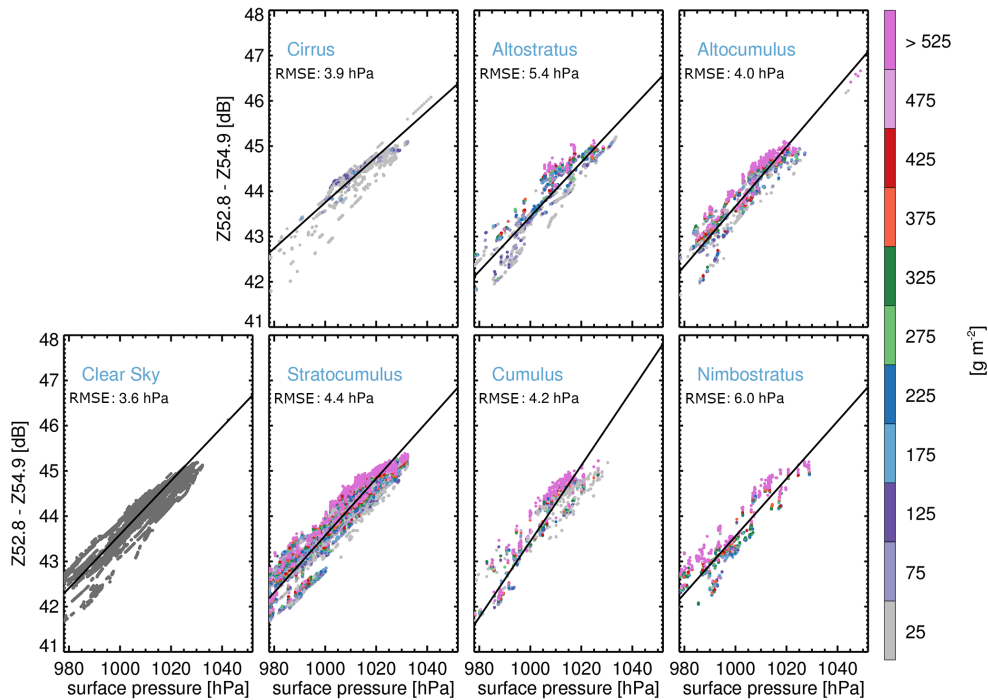


Figure 4. Simulated relationships between surface radar returns and surface pressure. Each point represents a CloudSat-driven simulation for each of the CloudSat measurements available in 15 January 2007 (clear-sky and cloudy cases only). The total hydrometeor column (for these cases IWC + LWC only) is color-coded. Dark gray is used for clear-sky cases (total hydrometeor column equal to zero). The root-mean-square error (RMSE) displayed is the overall linear regression error (black line) when fitting all the cases for each scenario.

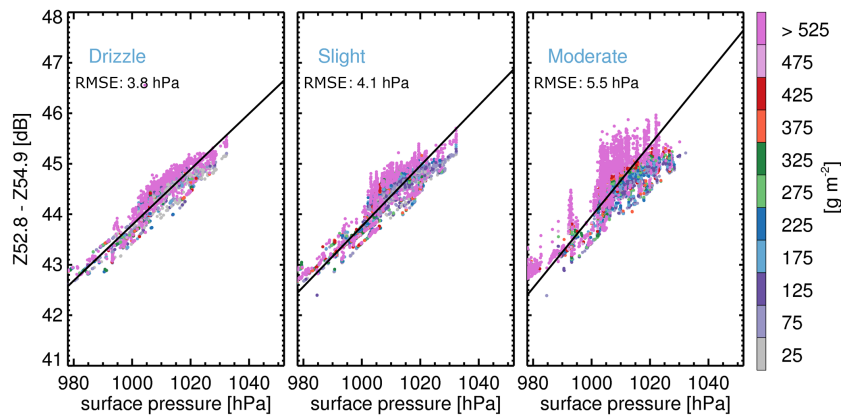


Figure 5. As in Fig. 4 but for precipitating cases. In this case, the total hydrometeor column includes IWC, LWC, rain, and snow. Drizzle, slight, and moderate correspond to rain rates lower than 0.1 , between 0.1 and 1 , and between 1 and 10 mm h^{-1} , respectively.

temperature, pressure, water vapor, and ozone from the European Centre for Medium-Range Weather Forecasts auxiliary (ECMWF-aux) products. A description of the 2B-GeoProf measurements and the 2B-CWC-RO R04 and 2C-RAIN-PROFILE retrievals can be found in Marchand et al. (2008), Austin et al. (2009), and Lebsock and L’Ecuyer (2011), respectively. The ECMWF-aux data are ECMWF model outputs interpolated in time and space to the CloudSat measurements (Partain, 2007). Furthermore, we also use the

2B-CLDCLASS product (Sassen and Wang, 2008) for cloud classification.

For each validation scenario, the hydrometeors (IWC, LWC, rain, and snow) retrieved by CloudSat as well as the interpolated ECMWF model outputs (temperature, pressure, water vapor and ozone) were used as forward model inputs. Then, the forward model results were compared with the corresponding CloudSat returns that were used to retrieve such hydrometeors in the first place. Figure 2 shows

Table 1. Systematic uncertainties perturbations*.

Perturbation	Amount	Comments
Temperature	3 K	Calculated as the average of 10 randomly perturbed profiles
Water vapor	10 %	Applied at all heights
IWC error	50 %	–
LWC error	50 %	–
Rain error	50 %	–
Snow error	50 %	–
IWC PSD1	–	Heymsfield et al. (2002)
IWC PSD2	–	Donovan and van Lammeren (2002)
LWC PSD1	–	Lognormal distribution with a 6 μm mean radius and a 1.5 spread.
Rain PSD1	–	Marshall and Palmer (1948)
Rain PSD2	–	Willis (1984)
Snow PSD1	–	Gunn and Marshall (1958)
Surface wind	12 m s^{-1}	–

* For the “unperturbed” characteristics see Sect. 3.

a comparison between the forward model run and CloudSat measurements under two scenarios, a cirrus and a precipitating case (rain rate $> 1 \text{ mm h}^{-1}$). In both cases, the forward model matches the CloudSat return, suggesting that the forward model assumptions are similar to the assumptions made in the CloudSat forward models used in such retrievals. Around 300 scenarios were simulated with an root-mean-square error (RMSE) of $\sim 3.5 \text{ dB}$.

4 Forward model simulations

Figure 3 shows clear-sky simulated differential radar surface returns between 52.8 (with return values of around 40 dBZ) and 54.9 (with return values of around $\pm 1 \text{ dBZ}$) GHz and surface pressure under three thermal and three water vapor conditions. These radar tones are used because they were selected by Lin and Hu (2005) as the best combination among a subset of six tones. As shown, there is a linear relationship between the differential radar surface returns and surface pressure. The slope of this curve is the exploitable signal, which is on the order of 1 dB/20 hPa. This figure shows that this signal is essentially insensitive to atmospheric water vapor burden but demonstrates a large sensitivity to the atmospheric temperature, which affects the pressure broadening of the lines within the oxygen band. In particular, it is the temperature close to the surface that influences the signal the most.

To investigate the effect of clouds and rain, as in Sect. 3.6, we use CloudSat-driven simulations (i.e., using IWC, LWC, rain, snow, temperature, pressure, water vapor, and ozone from CloudSat products) using data from 15 January 2007. We subset the data into clear-sky, cloudy, and rainy scenarios using the CloudSat cloud classification product as well as the rain rate estimate. Figures 4 and 5 display clear-sky,

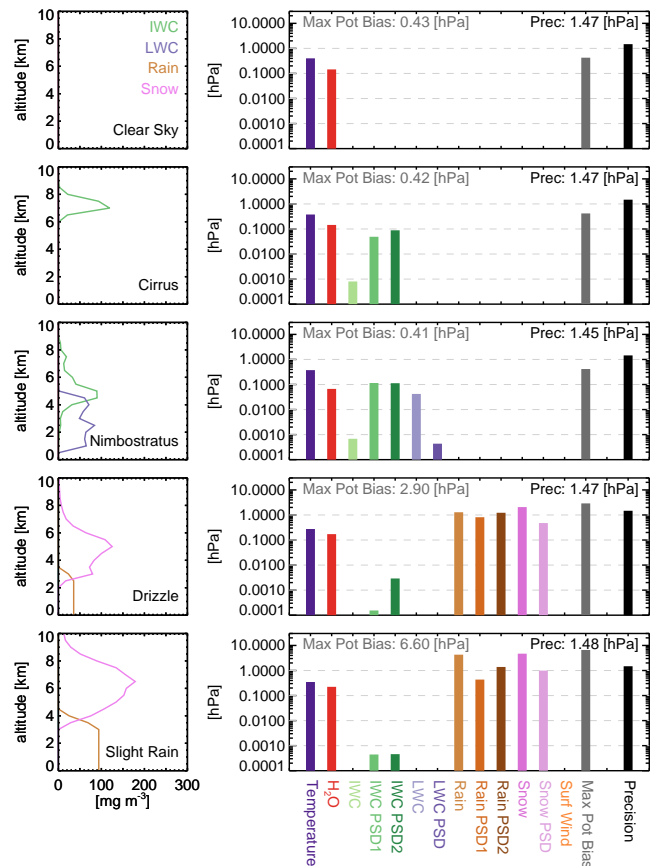


Figure 6. Systematic error estimates caused by each of the sources described in Table 1 as well as the precision and maximum potential bias for five different scenarios (clear sky, cirrus, nimbostratus, drizzle, and slight rain). The maximum potential bias is the root-sum-square combination of all the error sources shown. These simulations were performed using 52.8 and 54.8 GHz radar tones; simulations using optimum frequencies are shown in Fig. 8.

cloudy, and rainy simulated relationships between differential radar surface returns and surface pressure. As shown, there are good linear relationships between the differential radar returns and surface pressure even under moderate rain conditions. The RMSE in surface pressure varies from 3.6 to 6 hPa using scenario-by-scenario linear regressions. For example, an RMSE of 4.4 hPa was found by a linear regression using all the stratocumulus simulations. Under clear-sky conditions, the spread found in these simulations is due to the different background conditions, in particular temperature, as demonstrated in Fig. 3. For cloudy and rainy conditions, the spread results from a mixture of different background conditions plus different hydrometeors. The hydrometeor influence is most evident in the moderate rain subplot.

The results shown in Figs. 4 and 5 are encouraging. They demonstrate that even with no ancillary knowledge of the atmospheric temperature or cloud scenario, surface pressure can be constrained to within a few hectopascals. Of

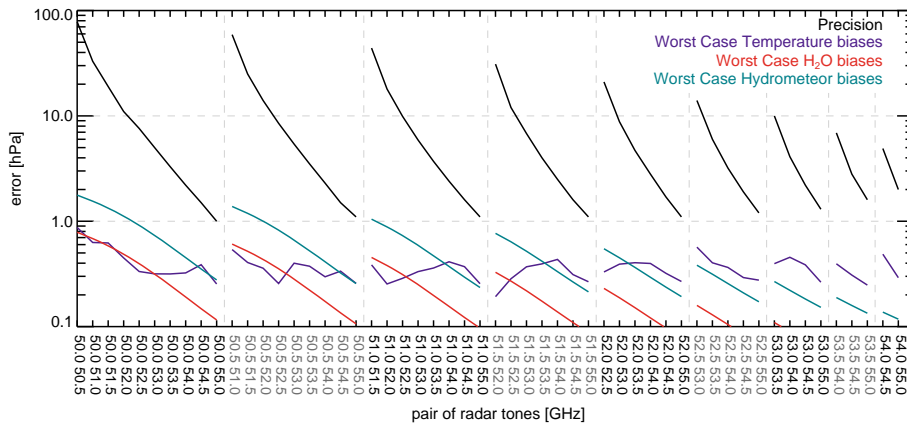


Figure 7. Precision and potential biases for the nimbostratus case shown in Fig. 6 using all the possible combinations between 50 and 55 GHz every 0.5 GHz. The hydrometeor bias is the root-mean-square sum of the errors labeled IWC, IWC PSD1, IWC PSD2, LWC, LWC PSD, Rain, Rain PSD1, Rain PSD2, Snow, and Snow PSD in Fig. 6.

Table 2. “Optimum” radar tones.

Scene type	Radar tones (GHz)	Precision ^a (hPa)	Potential bias ^a 80 % of the time (hPa)	Potential bias ^a 90 % of the time (hPa)
Clear sky	50.0, 55.0	1.1	0.45	0.45
Cirrus	50.0, 55.0	1.1	0.45	0.50
Altostratus	50.0, 55.0	1.1	0.50	0.70
Altostratus	50.0, 55.0	1.1	0.50	0.70
Stratocumulus	50.0, 55.0	1.1	0.55	0.90
Cumulus	50.0, 55.0	1.1	0.70	1.10
Nimbostratus	50.0, 55.0	1.1	0.70	1.00
Drizzle ^b	53.5, 55.0	1.6	1.35	1.65
Slight rain ^b	54.0, 55.0	2.1	1.80	2.35
Moderate rain ^b	54.0, 55.0	2.1	2.75	3.35

^a Estimates computed using end-to-end retrievals for each of the CloudSat measurements available in 15 January 2007 (Figs. 9 and 10). ^b Drizzle, slight, and moderate rain correspond to rain rates lower than 0.1, between 0.1 and 1, and between 1 and 10 mm h⁻¹, respectively.

course, such naive assumption is not expected, as operational weather analysis can provide reasonable constraints on the atmospheric temperature and a range gated radar system would itself provide information on the cloud/precipitation scenario. Note that subsetting the data using this ancillary knowledge will reduce the RMSE.

5 Error characterization and tone selection

To further study the capabilities of this technique, end-to-end retrievals were performed using 1 day of CloudSat-driven simulations as synthetic measurements. The retrieval algorithm used was a least-squares fit following Rodgers (2000) and assuming hydrostatic equilibrium. These retrievals allow us to quantify both the precision and accuracy of the surface pressure retrievals when using ancillary knowledge of

the atmospheric temperature or cloud/precipitation scenarios. The precision reflects the contribution from the measurement noise. The accuracy reflects systematic error sources, such as the error due to the assumed temperature profile, the error due to the characterization of particulate extinction ($\sigma_{\text{Pext}}(\lambda, s)$) or the error due to the characterization in the surface backscatter ($\sigma^0(\lambda)$) properties.

The accuracy errors were estimated by means of an end-to-end retrieval exercise. Starting with a set of conditions regarded as truth, we computed synthetic radar returns that were used as measurements and run through the retrieval algorithm. The retrieved surface pressure is regarded as a base for the comparisons. This set of conditions includes the pressure, temperature, gas concentration, and hydrometeor vertical profiles, as well as perfect knowledge of the hydrometeor PSDs and surface backscatter (all these assumptions are described in Sect. 3). Then, for each systematic error

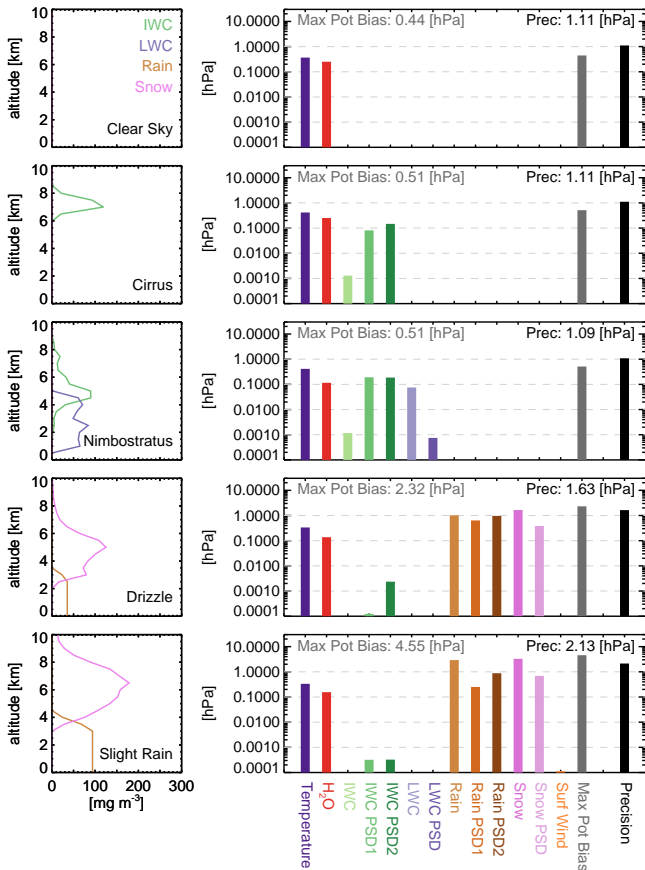


Figure 8. As Fig. 6 except these simulations were performed using the radar tones listed in Table 2.

a perturbed set of synthetic measurements were generated and run through the retrieval algorithm. For instance, when computing the systematic uncertainty related to temperature, only the temperature values were perturbed, while the rest (IWC, LWC, rain, snow, PSDs, etc.) were left unperturbed. The surface pressure retrieved for each of these perturbations is then compared to the base case. Table 1 summarizes the perturbations used. The spectroscopic uncertainties such as the errors due to the atmospheric absorption continuum (O₂, N₂, H₂O), the line strength, and line width, as well as the line mixing due to close spacing of the O₂ lines around the 60 GHz spectral region, will be investigated in a future study but presumably their impact will be small (i.e., given the successful DAR measurements from Flower and Peckham, 1978, and Lawrence et al., 2011), and calibrated out as part of a vicarious calibration campaign and can be better bounded through dedicated laboratory measurements.

Figure 6 shows the result of the uncertainty characterization for surface pressure retrievals under five different scenarios using 52.8 and 54.9 GHz radar tones. Using these particular tones with 0.05 dBZ instrument noise, the precision estimate was 1.5 hPa. In general, for all-sky conditions the most persistent potential error source was the assumed

temperature profile; this uncertainty results in biases of no more than ~ 0.5 hPa. In cloudy but non-precipitating situations this is followed by uncertainties due to errors in IWC and LWC as well as their corresponding PSD. For precipitating cases, the dominant source of uncertainty originates from errors in the rain and snow estimates as well as their corresponding PSD uncertainties; this can lead to worst-case biases as large as ~ 6.6 hPa. Lastly, uncertainties induced by possible errors in water vapor and surface wind (which change the surface backscattering) are negligible.

End-to-end retrievals allow us to select the radar tones which minimize the total error (precision plus accuracy). The precision can be thought of as a measure of the signal-to-noise ratio of the measurement system. As already shown (see Fig. 1 – top), atmospheric attenuation varies drastically near the 60 GHz O₂ band; the closer to the band center, the stronger the O₂ absorption. Clearly, positioning both radar tones near the absorption wings will provide no surface pressure information because the absorption for the two radar tones will be almost equal. Tones close to the band center will provide no information because they are fully attenuated. Hence, frequencies with moderate O₂ absorption carry the most potential surface pressure information. Furthermore, these moderately O₂ absorbed frequencies should be spaced as far apart as possible to increase their spectral contrast, which translates to a better differential signal and therefore improves the precision of the retrieved surface pressure.

As a demonstration of the tone selection process, we highlight the nimbostratus case shown in Fig. 6. Figure 7 shows the precision and potential biases using all the possible combinations between 50 and 55 GHz every 0.5 GHz. As expected, precision increases with tone spectral separation; specifically 50 and 50.5 have the worst precision while 50 and 55 have the highest precision.

Also shown in Fig. 7 are the potential biases due to temperature, water vapor, and hydrometeors. In principle, these biases should increase with tone separation because the spectral differences in the target optical properties increase (see Fig. 1). However Fig. 7 demonstrates that the increase in signal with tone separation dominates the potential increase in these biases. In general, this results in a decrease in retrieval biases with tone separation. Nonetheless, we note that the smallest hydrometeor and H₂O potential biases are found using 54 and 55 GHz, the two closest radar tones still containing pressure information.

In general, this suggests that the best pair of radar tones will depend upon the magnitude of the potential biases: (1) if they are considerably smaller than the precision, the best combination will be 50 and 55 GHz; (2) if they are significantly greater than the precision; the best pair of tones will be 54 and 55 GHz; and (3) if they are comparable to the precision, the best pair will be such that both of them are as similar as possible.

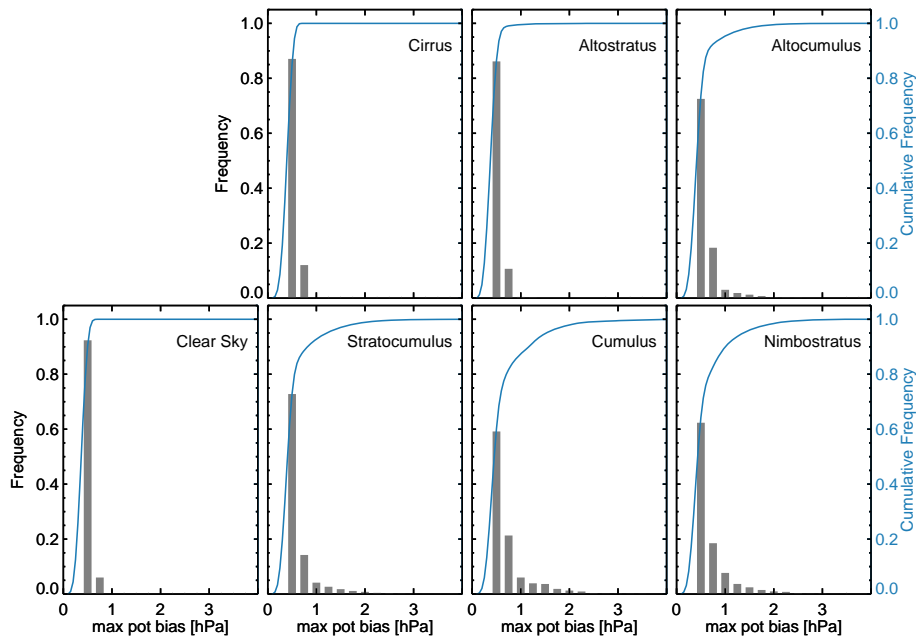


Figure 9. Histogram (gray) and cumulative histogram (blue) of the maximum potential biases for CloudSat-driven end-to-end retrievals for each of the CloudSat measurements available in 15 January 2007 (clear-sky and cloudy cases only).

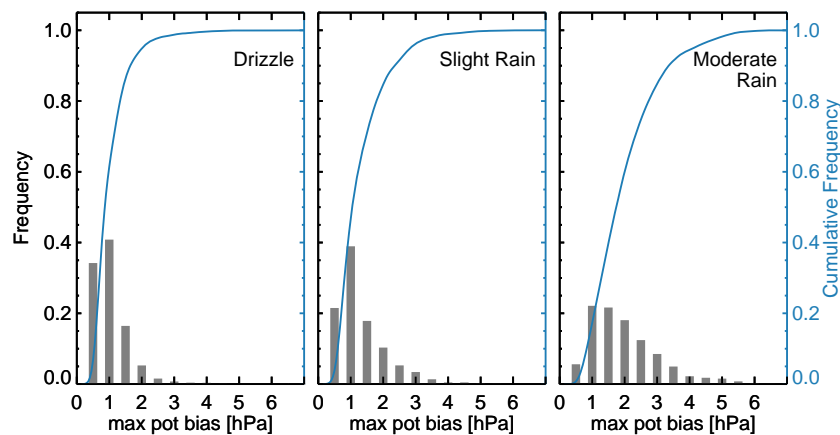


Figure 10. As in Fig. 9 but for precipitating cases.

To quantify this general conclusion for specific types of scenario we repeated this tone selection process for clear-sky, cloudy, and precipitating conditions, constructed from CloudSat representative profiles spread through 2007. For each scene type, around 30 cases were selected. As expected, for non-precipitating cases, the best combination was 50 and 55 GHz because the hydrometeor potential biases were small. For drizzle, the best combination was 53.5 and 55 GHz, because the hydrometeor potential biases had comparable levels to the precision. Lastly, for slight and moderate rain, where the error budget was dominated by the hydrometeor potential biases, we found that the best combination was 54 and 55 GHz.

The effects of using the optimum tone selection are shown in Fig. 8, which summarizes the result of the uncertainty characterization under the same scenarios shown in Fig. 6. Overall, the estimates of precision and the maximum potential biases decreased: for cloudy cases, precision improved to ~ 1.1 hPa (~ 0.4 hPa better than in Fig. 6), and for slight rain, the maximum potential biases due to hydrometeors decreased to ~ 4.5 hPa (~ 2 hPa less than before). Note that these radar tones are optimum in the sense that they should minimize the errors in a general sense; however there may be pairs of radar tones better suited for individual cases.

To test this technique under a wide range of conditions, end-to-end retrieval simulations were performed for all the available CloudSat measurements from 15 January 2007 using the optimum tones. Under clear-sky and cloudy conditions the precision of all the retrievals was improved to ~ 1.1 , under drizzle rain it was ~ 1.6 , and under slight and moderate rainy conditions it was ~ 2.1 hPa. Figures 9 and 10 show clear-sky, cloudy, and precipitating maximum potential biases histograms. The potential biases 90% of the time for clear-sky and cloudy conditions will be less than ~ 1.1 , for drizzle and slightly rainy conditions they will be less than ~ 2.4 , and for moderate rain they will be less than 3.4 hPa. Table 2 also lists the precision and potential maximum bias for each scene type. Note that, due to the differential nature of this technique, even though all the simulations were performed using an ocean backscatter model, these results are expected to be similar over land because the land surface backscattering coefficient ($\sigma^0(\lambda)$) is also weakly dependent on wavelength within the region of interest. These results demonstrate that this technique holds considerable potential as a method for retrieving surface pressure under realistic clear sky through moderate precipitating scenarios. Furthermore, these measurements should provide useful constraints for numerical weather forecasting (Flower and Peckham, 1978; Lin and Hu, 2005), closing the large gaps in the measured surface pressure coverage, particularly over the oceans. The quantitative impact of these measurements needs to be investigated using Observing System Simulation Experiments (OSSEs) or similar techniques to study the impact on data assimilation and forecast system performance.

6 Summary and conclusions

We have discussed the theoretical capabilities of a differential absorption radar technique to retrieve surface pressure under clear-sky, cloudy, and precipitating conditions. It was established that the differential radar returns near to the 60 GHz O₂ absorption region mostly depend upon surface pressure and temperature distribution. From this, it follows that, assuming a temperature distribution, it should be possible to invert a set of radar tones to retrieved surface pressure.

An inversion scheme was implemented focusing on the retrieval propagation of systematic biases as well as random errors (the retrieval precision). This provided a tool to weight the surface pressure signal against errors introduced by uncertainties in other parameters needed by the retrieval such as the assumed temperature distribution, hydrometeor abundances, and particle size distributions.

To find optimum radar tones for different scenarios (cirrus, altostratus, altocumulus, stratus, stratocumulus, cumulus, and nimbostratus, as well as drizzle, slight, and moderate rain), an ensemble of around 30 cases for each scenario was constructed using CloudSat data. Then, end-to-end retrievals were performed using all possible pairs of radar tones

between 50 and 55 every 0.5 GHz. Ultimately, the best pair of radar tones depends upon the magnitude of the potential biases. For biases smaller than the precision uncertainty, the best pair is 50 and 55 GHz, which increases the spectral contrast hence reducing the precision error. This is typically the case for clear-sky and cloudy scenarios. For biases greater than the precision uncertainty, the best pair is 54 and 55 GHz, which reduces the impact of the variation in particulate extinction with frequency. This is typical for slight and moderate rain scenarios. Lastly, for biases comparable to the precision, the best pair is such that both the precision and the biases are minimized.

Finally, using these optimum sets of radar tones, we inverted a whole day of CloudSat measurements to show the capabilities of this technique under a wide range of conditions. Our results suggest a minimal radar system with tones at 50 and 55 GHz to maximize precision in the prevalent non-precipitating scenarios. Addition of a third tone at 54 GHz would provide an optimum platform for retrievals with precision better than 2 hPa in all-sky conditions and commonly ~ 1 hPa. Generally, worst-case scenario biases will be less than 2 hPa, typically 0.5 and 1 hPa for non-precipitating and precipitating conditions. These results demonstrate that this technique holds considerable potential as a method for retrieving surface pressure under a realistic clear sky through moderate precipitating scenarios.

Future research will investigate the feasibility of using not only the surface returns but also the atmospheric returns due to the hydrometeors in a given scene to invert vertical pressure profiles. This may allow us to derive the atmospheric scale height and thus the temperature profile in the lower troposphere.

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