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Optimal frequency selection of multi-channel O_2-band different absorption barometric radar for air pressure measurements

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ABSTRACT

Through theoretical analysis, optimal selection of frequencies for O_2 differential absorption radar systems on air pressure field measurements is achieved. The required differential absorption optical depth between a radar frequency pair is 0.5. With this required value and other considerations on water vapor absorption and the contamination of radio wave transmission, frequency pairs of present considered radar system are obtained. Significant impacts on general design of differential absorption remote sensing systems are expected from current results.

1. Introduction

In general meteorology and atmospheric sciences, air pressure is a basic physical variable required in calculations of atmospheric dynamics and essential for greenhouse gas volume mixing ratio (or mole fraction) estimations [1]. Currently, surface air pressure can only be observed by in-situ instruments in extremely limited places (c.f., [2–4]). For example, air pressure over oceans can only be measured by sparsely distributed buoys, ships, and, occasionally, by dropsondes from aircraft; this sporadic distribution introduces considerable surface air pressure uncertainties in numerical weather prediction (NWP) and climate analysis/reanalysis models, especially for the model grid-boxes away from shipping lanes or coasts. Lack of sufficient observations of air pressure introduces huge societal impacts. A typical case is for extreme weather events such as tropical storms. Tropical storms, especially hurricanes, produce dangerous winds, torrential rains and floods, and are leading natural disasters in property damages and life losses. Accurate forecasts of their tracks and intensities well ahead of their landfalls will significantly reduce life losses and unnecessary socioeconomical burdens caused by evacuation and other hurricane responses of social communities that are not at risk. Essential physical processes that drive severe weather (e.g., hurricanes and tornados) are neither fully understood nor adequately characterized in weather forecast models. High priority is placed on measurements that will lead to successful forecasts of such events. As atmospheric pressure gradients are the primary driving force of atmospheric motions that transport mass, moisture and momentum (e.g., [1]), NWP models are critically dependent on accurate estimates of the pressure field. The pioneering concept [2] that remotely senses global surface air pressure fields using an O_2-band Differential-absorption BArometric Radar (DiBAR) provides a great potential to fill the pressure observation gap. With the NWP Weather and Research Forecast three dimensional variational data assimilation system in Observing System Simulation Experiments (OSSEs), substantial forecast improvements are found not only in the hurricane

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track and position, but also in the hurricane intensity as reflected in the maximum surface winds [3,4].

Because of the extreme importance of tropical storm forecasts for the society, rapid progress in DiBAR technique and technology is critical to the people and nation besides the OSSE efforts on DiBAR performances in improvements of hurricane forecasts, especially on tracks and intensities [3,4]. Thus, since the pioneering work on the DiBAR concept [2], NASA Langley Research Center, with supports from academic institutes and industry companies, has formulated a surface barometry concept, developed a DiBAR system design, fabricated a Prototype-DiBAR (P-DiBAR) instrument for proof-of-concept, and conducted lab, ground and low altitude aircraft tests of the P-DiBAR instrument [5–7]. The flight test results clearly demonstrate the consistency between theoretical analyses of the DiBAR concept and remote sensing measurements of the barometric pressure radar, and show that current DiBAR technology provides a great potential of global precise surface air pressure measurements from space.

Although significant progress has been made, there is room for improvement in the instrument development. The P-DiBAR instrument is based on the concept of general differential absorption measurements with radar return from 50 to 60 GHz. While for space and high altitude operational science instruments, their systems need to be optimized at the best performance point with a finite set of operation frequencies. Frequency selection provides the chance for this optimization. Also, as an active instrument, DiBAR needs to control its transmission and avoid radio wave contamination potentials to passive microwave satellite measurements such as those from Advanced Microwave Sounding Unit (AMSU) operating at the O_2-band. This study focuses on the system optimization and frequency selection of DiBAR instrument and provides a guideline for the future work on the system design of differential absorption remote sensing instruments.

2. Measurement approach and system optimization

Since the measurement approach, instrumental system structure, and the developed P-DiBAR sensor were discussed in previous reports [2,6], we only briefly review key characteristics of DiBAR approach and pave the way of optimization. The DiBAR instrument is based on the measurements of differential absorption of radar returns at the 50–70 GHz O_2-band. This O_2-band has extremely large absorption dynamics with optical depth reaching as high as 200 db. To avoid excessive loss of radar power, only frequencies at 50–55 GHz are considered [2]. Since O_2 is generally well-mixed with other gases in the atmosphere, the column O_2 amount observed by a radar is proportional to column air mass, thus, to the surface air pressure.

Assuming the transmitted radar power is P_0, the received radar power P_f at frequency f from surface at range R can be expressed as [2]:

$$P_f = C\rho P_0 (T_f T_c T_g)^2 / R^2, \tag{1}$$

here C is a measurement system constant, ρ is the surface reflectance. T_f and T_c are atmospheric transmissions due to the O_2 absorption at the frequency f and the cloud extinction, respectively. T_g is for the absorption from gases other than O_2, which is very weak and dominantly decided by water vapor due to its continuum absorption and far wing spectra of 22.2 GHz weak absorption line. For two radar returns of very close frequencies f_1 and f_2, the absorption from other gases, cloud extinction and surface reflectivity for the radar power are virtually the same. Thus, the power ratio of radar returns from the same target is:

$$P_1/P_2 = (T_1/T_2)^2 = e^{-2\tau}, \quad or \quad \tau = -0.5Ln(P_1/P_2) = -0.5Ln(\eta), \tag{2}$$

where τ is the O_2 differential absorption optical depth (DAOD) between frequencies 1 and 2, and η is equal to P_1/P_2, the key signal that needs to be measured by DiBAR system. This shows that the first requirement of frequency selection is very small frequency shifts (within ~3 GHz) for differential absorption radar wavelength pairs at 50–55 GHz band to minimize the changes in continuum absorption (this O_2-band is already far away for the weak 22.2 GHz absorption line). The second consideration is for signal strength of radar return powers. Because the frequencies selected are within 50–55 GHz range, excessive absorption is avoided and sufficient signal powers can be obtained with existing radar technology [2,6]. More critically, the consideration is for the signal-to-noise ratio (SNR or γ) of DAOD. Since surface pressure is estimated from DAOD measurements, for precise surface pressure observations, a DiBAR design needs to have the SNR optimized.

From Eq. (2) and assuming $\delta\tau$ and $\delta\eta$ are the measurement uncertainties in τ and η, respectively, we have:

$$\delta\eta = -e^{-2\tau} 2\delta\tau = -2\eta\, \delta\tau. \tag{3}$$

As expected, this result shows that the uncertainties in DAOD (or O_2 amount and surface pressure) measurements are directly determined by the uncertainties in DiBAR power measurements. Note that for measurement uncertainty consideration, the absolute values for $\delta\tau$ and $\delta\eta$ are practically useful. Furthermore, it can be shown that the SNR of DAOD γ is proportional to the product of DAOD and the measured signal η *or* $e^{-2\tau}$. From Eq. (3), we have

$$\gamma = \tau/\delta\tau = 2\tau/(2\delta\tau) = -2\tau\eta/\delta\eta = -2\tau e^{-2\tau}/\delta\eta. \tag{4}$$

For general measurement environments and the O_2-band DiBAR system, the uncertainty in measurement signal or $\delta\eta$ can be assumed to be at a constant level. Thus, we define the variable part of γ as K, $K = \tau e^{-2\tau}$. To obtain highest SNR, we evaluate K for the maximal SNR on the differential absorption optical depth τ:

$$dK/d\tau = e^{-2\tau} - 2\tau e^{-2\tau} = 0, \text{ or } 1 - 2\tau = 0. \tag{5}$$

Thus, $\tau = 0.5$. Around this τ value, the second derivative of K is:

$$d^2K/d^2\tau = -2e^{-2\tau} - 2e^{-2\tau} + 4\tau e^{-2\tau} = -4e^{-2\tau}(1-\tau) < 0 \tag{6}$$

when $\tau < 1$. Thus, we have a highest SNR when two-way DAOD between frequencies 1 and 2 is equal to 1. Based on Eq. (4), the SNR of DAOD would be equivalent to the SNR of the power ratio of radar returned signals at this τ value. That is, the designed DiBAR system would provide best retrievals of O_2 DAOD from the estimates of radar power ratio. This result also shows that at this 2-way DAOD 1, not only there are sufficient high differences between the radar returns of the two frequency channels for measuring O_2 amounts, but also atmospheric O_2 absorption is not too high to cause excessive attenuation on radar transmitted power. So, the best DAOD SNR would be obtained directly from the best power measurements.

With these considerations, a newly developed passive and active microwave vector radiative transfer (PAM-VRT) model [8] has been used to analyze the spectral characteristics at the O_2-band. The PAM-VRT consists of five modules: gas absorption, hydrometeor property, surface emissivity, vector radiative transfer, and passive and active microwave instrument simulators, with flexible and versatile input and output components. These models also address the crucial issues such as the uncertainties in hydrometeor's scattering, temperature dependence of cloud liquid water absorption and water vapor continuum absorption in microwave radiation considered previously [10,11]. The vector radiative transfer of successive order of scattering (VSOS) model [9] is used with the post-processing source function, enabling accurate simulations of microwave sensors with any particular view geometry, such as DiBAR. Fig. 1 shows the optical depth values of total gas absorption, O_2 absorption, water vapor absorption, and liquid water absorption as a function of frequency for the US standard atmosphere. It can be seen that water vapor absorption optical depths are at least one order of magnitudes smaller than oxygen absorption depths between 50 and 60 GHz, and the impact of water vapor absorption on DAOD would be further minimized when close frequency pairs are selected. Additionally, fine correction on the difference of water vapor optical depth at the paired frequencies would be obtained with column water vapor amount data which are available from passive remote sensing sensors. With all these considerations water vapor influence would be reduced to negligible level in pressure measurements. Cloud and precipitation hydrometeors absorb and scatter microwave radiation. For most clouds (without heavy precipitation), the cloud effect would be minimal for the differential radar return due to the lack of strong attenuation and similarity of cloud optical properties within the narrow frequency difference of the frequency pair.

Although a sufficient dynamic range of O_2 absorption is provided at this microwave band, there is a significant complexity in absorption structure due to multiple absorption lines within this complex. To obtain best pairs of frequency lines, we generally select the radar frequencies:

a) At smooth spectral regions to avoid the complexity of multiple absorption lines and/or steep changes in absorption strength near line centers
b) Outside existing microwave sensor frequency bands, such as AMSU, to avoid potential contamination.
c) Multiple frequency pairs with different O_2 absorption strengths to enhance the resolving power of surface pressure for different (low and high) surface pressures at different latitudes and elevations

To enhance the resolving power of surface pressure for different latitudes and elevations, we select six frequencies to form four frequency pairs with different O_2 absorption strengths. Table 1 lists all six frequencies considered for DiBAR. The DAOD values for individual frequency pairs in the table are around 0.5 to reach optimal O_2 column measurements. It can be seen that the difference in water vapor absorption optical depth is significantly smaller than its corresponding O_2 DAOD value and satisfies our basic pressure retrieval requirements. Also, a DiBAR with these frequencies certainly would not generate significant radio frequency contamination for passive microwave remote sensing and have optimized SNR for remote air pressure measurements.

Table 1
Optical depths of six frequencies (within ± 0.01 GHz) and four frequency pairs of F1-F2, F2-F3, F3-F4, F5-F6.

Frequency (GHz)	Total-OD	O_2-OD	H_2O-OD
50.011	0.35163	0.31086	0.03932
52.341	0.85421	0.81069	0.04193
53.018	1.3567	1.3123	0.04272
53.396	1.7497	1.7048	0.04319
54.595	4.8262	4.7797	0.04479
54.643	5.3242	5.2776	0.04486

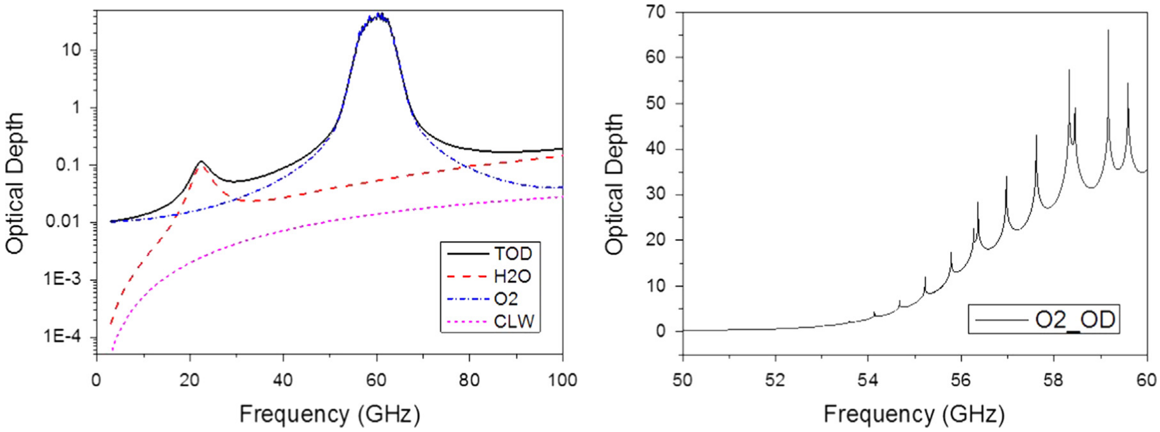

Fig. 1. Optical depths of total (TOD) absorption, oxygen (O_2) absorption, water vapor (H_2O) absorption, and cloud liquid water (CLW) absorption as a function of radar frequency.

3. Summary

Through analytic studies, a procedure of optimal selection of DiBAR frequencies is obtained. One of the critical criteria is the differential absorption optical depth between a radar frequency pair should be about 0.5. The method and general conclusion of the optimization obtained by this work not only can be used in current DiBAR instrument design, but also have broad applications in other differential absorption remote sensing systems. The two-way DAOD 1 should become a standard for future differential absorption studies.

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