frontiers in Remote Sensing

PERSPECTIVE
published: 11 March 2022
doi: 10.3389/frsen.2022.796273

EPIC/DSCOVR as a Pathfinder in Cloud Remote Sensing Using Differential Oxygen Absorption Spectroscopy

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We argue that the Earth Polychromatic Imaging Camera (EPIC) on the Deep Space Climate ObserVatoRy (DSCOVR) platform has blazed new pathways in observational technology, starting with its ~ 1.5 × 106 km stand-off distance, but also in remote sensing science. We focus here on EPIC's two oxygen absorption channels that 1) are unique in their spectral sampling and 2) have stimulated deep innovation in cloud remote sensing using Differential Oxygen Absorption Spectroscopy (DO_2AS). Although first formulated 6 decades ago, DO_2AS-based cloud probing from overhead assets is still an emerging observational technique. It is indeed somewhat paradoxical that one should use absorption by a gas to assay scattering by particles. After surveying the history of space-based DO_2AS, and looking into its future, we see that EPIC/DSCOVR marks an inflection point in this important development. EPIC's unique DO_2AS capability motivated a notable sequence of papers revisited here. This research indeed spawned a rare occurrence of information content analysis coming from radically different—yet complementary—perspectives. First, we adopted the increasingly popular machinery of optimal estimation (OE) that is grounded in Bayesian statistics and uses a somehow linearized radiative transfer (RT) model. Nonetheless, OE feels like a black-box algorithm that outputs a number of "degrees of freedom" (a.k.a. independent pieces of information about clouds under observation). However, the very same conclusions are reached using fully transparent physics-based modeling for the RT, with a few approximations that enable closed-form analytical formulation. Lastly, we preview a novel DO_2AS technique for regaining shortwave sensitivity to cloud optical thickness past the threshold where cloud reflectivity flattens off.

Keywords: DSCOVR, EPIC, oxygen A-band, oxygen B-band, clouds, pathlength distribution, pathlength moments

OPEN ACCESS

Edited by:
Yongxiang Hu,
National Aeronautics and Space Administration (NASA), United States

Reviewed by:
Chao Liu,
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Specialty section:
This article was submitted to Satellite Missions, a section of the journal Frontiers in Remote Sensing

Received: *16 October 2021*
Accepted: *19 January 2022*
Published: *11 March 2022*

Citation:
Davis AB, Yang Y and Marshak A (2022) EPIC/DSCOVR as a Pathfinder in Cloud Remote Sensing Using Differential Oxygen Absorption Spectroscopy. Front. Remote Sens. 3:796273. doi: 10.3389/frsen.2022.796273

1 INTRODUCTION AND OUTLINE

Since the beginning of operational satellite meteorology, NASA's TIROS-1 (launched 1960), we have been accustomed to seeing clouds as a dynamical 2D map projected onto the Earth's surface. However, meteorologists and atmospheric scientists in general yearn for knowledge of clouds in the vertical dimension where complex processes in cloud physics unfold, from nucleation to precipitation. This unsatiable thirst for knowledge of the vertical distribution of clouds persists to this day. In fact it permeates NASA's 2017 Decadal Survey (National Academies of Sciences, Engineering, and Medicine, 2018) not only in the Designated Observables from the Aerosol/Cloud-Convection-Precipitation (ACCP) arena but also in the more experimental Planetary Boundary Layer (PBL) Incubator program.

The earliest known publications on the potential use of molecular absorption to determine cloud height are in a discussion initiated by Hanel (1961), just a year after TIROS-1's launch. He was indeed promptly engaged by Yamamoto and Wark (1961) and Chapman (1962) who suggest using the oxygen A-band (759–769 nm) because O_2 is a dominant constituent with a well-characterized pressure profile. Thus started the idea of using differential Oxygen absorption spectroscopy (DO_2AS), a special case of differential optical absorption spectroscopy (DOAS), to probe clouds from space.

In the following **Section 2**, we survey the history and geography of DO_2AS-based sensing of scattering particulates in the Earth's atmosphere from space. We focus on the period ending in 2010 because that is more-or-less when theory-dominated research is superseded by data-driven work since, by then, several satellites with O_2 A-band coverage were in orbit. To balance the theory-heavy literature survey, we describe more-or-less chronologically the core technological aspects of satellite missions so far with DO_2AS capability, underscoring EPIC/DSCOVR's uniqueness. Finally, we gaze into what lies ahead for O_2 absorption in satellite missions to be launched in the foreseeable future.

This leads to the lessons-learned from investigating the cloud information content of EPIC's (764 ± 0.2 nm) and B-band (687.75 ± 0.2 nm) channels using both physics and statistics in **Section 3**. From there, we connect the implicit dependence of EPIC's O_2 absorption channel responses on the mean pathlength of sunlight in the cloudy medium to recent advances in statistical physics. In turn, that deep dive into the fundamental physics of O_2 absorption in scattering media such as clouds reveals a new path toward the inference of cloud optical thickness (COT) for very opaque clouds from DO_2AS, not just through radiance levels in continuum channels that are soon saturated as COT increases.

We summarize in **Section 4**, and contemplate the future of DO_2AS observation of clouds from space.

2 BRIEF HISTORY OF SPACE-BASED DO_2AS, A LOOK INTO THE NEAR-FUTURE AND THE SPECIAL ROLE OF EPIC/DSCOVR

Soon after the first suggestion of using DO_2AS in cloud sensing (Yamamoto and Wark, 1961; Chapman, 1962), the mathematical connection between the *distribution* of light paths in scattering media and the detailed shape of the absorption spectrum was rigorously established (Irvine, 1964) This key development was followed by the physically-correct analogy with non-stationary radiation transport (Katsev, 1969; Katsev and Zege, 1974). Astrophysical theoreticians made important early contributions (e.g., Ivanov and Sabashvili, 1972; Nagirner, 1974). The earliest known observations of clouds from space in the O_2 A-band are from 1965, using a handheld camera operated aboard Gemini-5 (Saiedy et al., 1965; Saiedy et al., 1967; Wu, 1985). It seems that the first non-astronaut counterparts were performed by a sensor aboard Kosmos 320 in 1970 (Gorodetskiy et al., 1971; Syachinov and Kozlov, 1974), and possibly as early as 1967 with the near-identical Kosmos 149 (Malkevich, 1974).

At any rate, a considerable amount of research on cloud remote sensing using overhead DO_2AS was performed in the Former Soviet Union in the 1970s (Dianov-Klokov et al., 1970; Dianov-Klokov and Krasnokutskaya, 1972; Kargin et al., 1972; Malkevich et al., 1975; Dianov-Klokov, 1976; Grechko et al., 1976; Dianov-Klokov et al., 1977; Grechko, 1978), including observations from an aircraft (Grechko et al., 1973) and a satellite (Gorodetskiy et al., 1971; Syachinov and Kozlov, 1974), and into the 1980s (Badayev and Kozlov, 1980; Grechko et al., 1982; Romanova and Ustinov, 1982; Skorinov and Titov, 1984; Gusev and Dvoryashin, 1990). In the West, there was a fast-growing interest in O_2 absorption as a means of probing clouds during the 1990s (Fisher et al., 1991; Fisher and Grassl, 1991; O'Brien and Mitchell, 1992; Kuze and Chance, 1994; Asano et al., 1995; Hayazaka et al., 1995; O'Brien et al., 1999) and into the 2000s (Heidinger and Stephens, 2000; Partain et al., 2000; Stephens and Heidinger, 2000; Kokhanovsky et al., 2004; Kokhanovsky and Rozanov, 2004; Rozanov and Kokhanovsky, 2004), with an increasing emphasis on 3D RT signatures (e.g., Heidinger and Stephens, 2002; Kokhanovsky et al., 2007; Davis et al., 2009).

The above extensive but non-exhaustive literature survey of cloud-focused space-based DO_2AS ends in 2010. Indeed, by the end of the first decade of the 21st century, there were already several satellites in orbit collecting real DO_2AS data on clouds, as we will document in the following (**Table 1**). We therefore view 2010, somewhat arbitrarily, as the end of an era of theory-dominated research on space-based cloud remote sensing using DO_2AS and the beginning of data-driven research. Since then, activity in this field has of course continued to grow steadily. In view of this sustained growth, a Workshop on "Remote sensing in the O2 A-band" was convened at KNMI in de Bilt, Nederlands, in 2016. A Second Workshop on "Remote Sensing in Oxygen Absorption Bands" was planned to happen in Berlin, Germany, in 2020, but has been postponed because of the COVID-19 pandemic to a future date in 2022. At any rate, this shows that there is a well-defined scientific community engaged in DO_2AS, for clouds and from space in particular.

We can now take a more-or-less chronological stroll through satellite missions with imaging DO_2AS capability, whether or not implemented with clouds in mind.[1] We see five clusters emerge, with spectral sampling and spatial resolution being distinguishing factors. We distinguish between moderate and low spatial resolution based on the implicit definition of "moderate" (M)

[1]We pass on the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) on the OrbView-2 (a.k.a. SeaStar) satellite mission, from 1997 to 2010. Its channel 7 (745–785 nm) covers the O_2 A-band but it was never exploited for atmospheric scattering. In fact, the O_2 absorption was a minor impediment for the targeted ocean color sensitivity that was eventually "corrected" out of the signal (Wang, 1999).

TABLE 1 | Compendium of satellite missions with DOAS capability ordered chronologically and clustering sensors with similar characteristics. To the best of our knowledge, SCIAMACHY is the first instrument with an operational DO_2AS-based cloud product (Kokhanovsky et al., 2005), followed by the POLDER series (Buriez et al., 1997; Vanbauce et al., 1998) and EPIC (Yang et al., 2019). Research cloud property retrievals have been developed for these missions, e.g., MOS-A (Preusker et al., 2007), POLDER-3 (Ferlay et al., 2010), and others, most recently, OCO-2/3 (Richardson et al., 2017; Richardson and Stephens, 2018; Richardson et al., 2019; Richardson et al., 2020). Such experimental retrievals can and have been transitioned into fully operational elements in the data processing pipeline.

Sensor Name	Developed by ...	Platform	Agency	Dates	Spatial resolution	Spectral Sampling	Multi-view?	Reference
GOME	DLR	ERS-2	ESA	**1995**–2011	VL	M	n	Burrows et al. (1999)
MOS-A	DLR	IRS-3	ISRO	1996–2004	M	M	n	Thyagarajan et al. (1996)
SCIAMACHY	SRON	Envisat	ESA	2002–2012	VL	M	n	Bovensmann et al. (1999)
GOME-2	DLR	MetOp-A/-B/-C	EUMETSAT	2006-/2012-/2018-	VL	M	n	Callies et al. (2000)
MERIS	ALCATEL	Envisat	ESA	**2002**–2012	M	2C	n	Rast et al. (1999)
POLDER	CNES	ADEOS I	NASDA	1996–1997	L	2C	y	Deschamps et al. (1994)
POLDER-2	CNES	ADEOS II	NASDA	2002–2003	L	2C	y	
POLDER-3	CNES	PARASOL	ESA	**2004**–2013	L	2C	y	
OCO-2	JPL		NASA	**2014**-	M	VH	n	Crisp et al. (2008)
OCO-3	JPL	ISS	NASA	2019-	M	VH	n	Eldering et al. (2019)
OLCI	ACRI-ST	Sentinel-3A/B	ESA	2016-/2018-	M	M	n	Nieke et al. (2012)
EPIC	GSFC	DSCOVR	NASA + NOAA	**2015**-	L	2C (A,B)	n	Marshak et al. (2018)

resolution used by MODIS (MODerate resolution Imaging Spectro-radiometer), namely, pixels that are on the order of 1 km in scale. By this standard, sensors with "low" (L) resolution have pixels on the order of 10 km in scale, and "very low" (VL) resolution sensors have pixels that are several 10s of km. We also distinguish "low," "moderate" and "very high" (VH) spectral resolutions: respectively, ~2-to-5, ~10s, ~1000s of spectral samples across the (~10 nm wide) A-band, all of which are useful. Alternatively, there is the "two-channel" (2C) strategy, typically in-band and out-of-band channels from which a single DOAS ratio can be formed; however, it can also be implemented with a narrow/in and broad/in-and-out pair of channels, as was done for POLDER (POLarization and Directionality of the Earth's Reflectances). Either way, in the 2C scenario, it is important to know if there are single or multiple views. **Table 1** displays satellite missions with DOAS capability that we have identified over the past two-and-a-half decades,[2] with some key defining characteristics and a reference for more information. Five clusters emerge.

EPIC's DO_2AS capability is new and unique in at least two respects in the realm of technology. First, it has an extreme standoff distance of ~1.5 10^6 km to the Lagrange-1 point. From there, the sensor sees almost all of the sunlit hemisphere all the time, i.e., there is no down-time. Additionally, EPIC uses a special spectral sampling strategy based on both the A- and B-bands of the di-oxygen molecule. The advantage in this is not, as we will see in the next section, that these bands have different absorption strengths. Rather, the surface albedo is low, hence less confounding for cloud probing, in at least one of these bands: over water, in both; over vegetated land, in the B-band.

The future of DO_2AS in space is bright, especially in Low-Earth Orbit (LEO). There will be two more OLCI/Sentinel-3 launches in the late 2020s, followed by ESA's TROPOMI/Sentinel-5 series (Veefkind et al., 2012)—with a precursor mission already launched in 2017. EUMETSAT will have a multi-angle/multi-spectral/multi-polarization imager (3MI) (Manolis et al., 2013), with POLDER (hence A-band) legacy, on all of its future MetOp second-generation satellites, starting in 2024. Moreover, EUMETSAT's Sentinel-4 series (Meteosat Third Generation, MTG), due to be launched in 2023 and 2030, will carry the S4 UVN Multispectral Spectrometer (Riedl et al., 2019) to Geostationary orbit (GEO), with the O_2 A-band covered at 0.12 nm resolution. Back in LEO, NASA/JPL's Multi-Angle Imager for Aerosols (MAIA) mission (Diner et al., 2018) will have a 2C/multi-angle take on the A-band at moderate spatial resolution. NASA's Plankton, Aerosol, Cloud ocean Ecosystem (PACE) mission (Werdell et al., 2019) will cover the A-band with two of its three sensors at relatively low spectral resolution:

- GSFC's Ocean Color Instrument (OCI) (Meister et al., 2019), with a moderate spatial resolution, and
- SRON's SPEXone (Rietjens et al., 2019), with a somewhat lower spatial resolution but offering multiple views and polarization across all wavelengths.

MAIA and PACE are scheduled to launch in the October 2024 – March 2025 timeframe. Last but not least, as part of NASA's next generation of Earth observing satellites, the Atmospheric Observing System (AOS) implements the 2017 Decadal Survey's ACCP element; it will include a UV-VIS imaging spectrometer in polar orbit that covers the O_2 A-band at low spectral and moderate spatial resolutions, with a launch date in the late 2020s.

[2]At first glance, **Table 1** seems to show that NASA was the last space agency to develop and launch satellite missions with DO_2AS capability as late as the mid-2010s. That is, however, far from true. Both NASA/JPL's CloudSat and the joint NASA/LaRC - CNES CALIPSO (co-launched into the A-train in 2006) were originally planned to have A-band imagers that were later descoped. With their inherent sensitivity to CTH, these A-band cameras would have extended at least CTH detection from the actively-probed sub-track "curtain" into the across-track direction.

3 INFORMATION CONTENT OF THE PATHLENGTH DISTRIBUTION

We contend that EPIC not only blazed a new path into the observational technology of DO_2AS from space, but also in the associated remote sensing science, which we view as enabling Earth system science via remote sensing. To make this point, we briefly revisit a series of papers motivated by EPIC's two pairs of DOAS channels for the A- and B-bands.

Even before the DSCOVR launch, Yang et al. (2013) devised a method for extracting two cloud properties from EPIC's two DO_2AS ratios, namely, cloud top height (CTH) and cloud geometric thickness (CGT). Specifically, the authors used the sum and difference *apparent* cloud heights from both ratios, where "apparent" refers to the fact that in-cloud propagation and scattering are not accounted for. However, the fact that they are different is precisely because of the finite pathlength cumulated inside the cloud and the different strengths of the A- and B-bands. Two-entry (CTH,CGT) look-up tables (LUTs) were therefore generated to retrieve the two cloud properties, much like how the Nakajima and King (1990) algorithm delivers cloud optical thickness (COT) and cloud particle effective radius given two reflected radiances, one VIS (with dominant sensitivity to COT) and one SWIR (with dominant sensitivity to particle size).

After the DSCOVR launch and EPIC's first light, it became clear to the cloud product team that it is important to factor into their algorithms the sensor's finite radiometric signal-to-noise ratio (SNR). Davis et al. (2018b) therefore followed the well-beaten path of optimal estimation (OE) theory (Rodgers, 2000) to do that. OE is, in essence, a formalism grounded in probabilistic information theory and linear algebra that relates measurement (Level 1) error and any prior/Baysian knowledge to retrieval (Level 2) error. OE has, at its core, a forward RT model that is either linearized or run at sufficient numerical precision to compute accurate Jacobian matrices by finite differencing. However, once implemented in code, the mathematical expressions of OE feel like a "black box" procedure that just has to be trusted. The authors concluded from their formal OE-based cloud information content analysis of EPIC's two DO_2AS ratios that CHT can be inferred with useful accuracy, but not CGT.

It is rare to have a second opinion on the assessment of geophysical information content of some set of measurements that is more transparent in nature, but this did occur for EPIC's two DO_2AS ratios. Indeed, Davis et al. (2018a) derived from first principles a model simple enough to be expressed in closed form, yet realistic enough to capture the main radiative processes unfolding from source to sensor. The authors used this physics-based approach to assess the sensitivities of EPICs DO_2AS ratios to CTH and CGT, bearing in mind the finite amplitude of the sensor noise, and they again found a strong response to CTH and a weak one to CGT.

In hindsight, the series of three papers published in the *Journal of Quantitative Spectroscopy and Radiative Transfer* weave a story about adjusting expectations to sensor and algorithm realities. In the case, it is about EPIC's ability to probe clouds: cloud top from O_2 absorption channel ratios and COT from the radiometrically-calibrated continuum channels, assuming either liquid or ice particles (cf. Yang et al., 2019), but unfortunately not cloud base height via CTH.

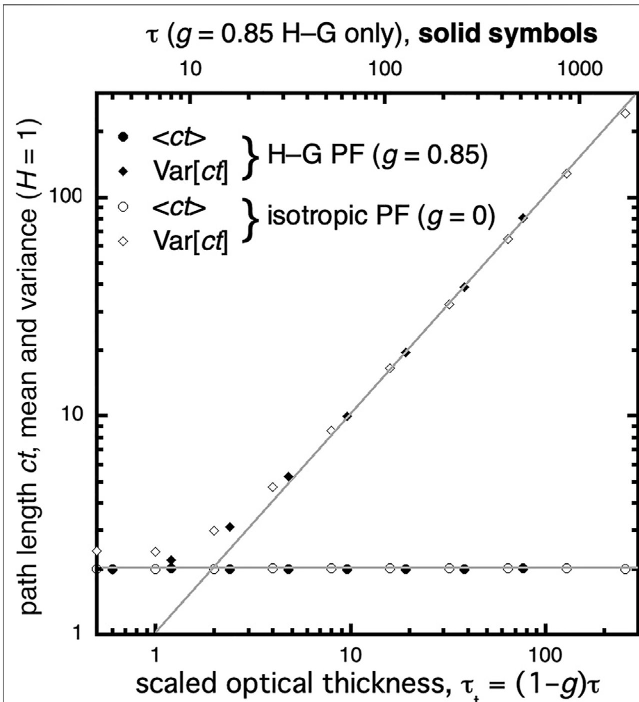

FIGURE 1 | Pathlength moments $\langle L \rangle$ and $\mathrm{Var}[L](\tau)$ are plotted versus τ in log-log axes. Symbols mark the Monte Carlo simulation results, while diffusion model outcomes are solid lines. The invariance of $\langle L \rangle$ is verified exactly. Furthermore, the diffusion-theoretical prediction that $\mathrm{Var}[L](\tau) = (1-g)\tau/2\chi$ (with extrapolation scale factor χ set to 2/3) becomes very accurate at $\tau_t = (1-g)\tau \sim 4$. Two phase functions were investigated: $g = 0$ (isotropic scattering) and $g = 0.85$ (forward-peaked Henyey and Greenstein (1941) scattering). Adapted from Davis et al. (2021), where $\langle L \rangle$ is denoted $\langle ct \rangle$.

That is not however the end of EPIC's influence on the remote sensing science of O_2 absorption observations in application to cloud profiling. By happenstance, EPIC's DO_2AS research team was alerted by N. Ferlay, an expert in POLDER's A-band information content, about a powerful invariance property of mean pathlength $\langle L \rangle$ cumulated *inside* a scattering optical medium of arbitrary shape and internal structure: $\langle L \rangle = 4V/S$, where V is the volume of the medium and S is its surface (Blanco and Fournier, 2003). This remarkable result is predicated on uniform and isotropic illumination of the medium, which clashes with the cloud-illuminated-by-the-sun scenario, and integration over all possible escape positions and directions, which conflicts with single direction sampled in remote sensing. There is nonetheless a strong message: once reduced to just in-cloud paths, $\langle L \rangle$ informs us directly about the size of the medium. For plane-parallel media, where V and S are infinite, $\langle L \rangle = 2H$, with H being the geometrical thickness of the slab.[3]

[3]Picture a finite cylinder with radius R and thickness H: $V = H\times(\pi R^2)$ and $S = 2\times\pi R^2 + H\times(2\pi R)$. As $R \to \infty$, $\langle L \rangle = 4V/S \to 2H$.

This begs the question about what pathlength variance $\mathrm{Var}[L] = \langle (L - \langle L \rangle)^2 \rangle = \langle L^2 \rangle - \langle L \rangle^2$ brings to the table in terms of cloud information. Blanco and Fournier (2006) show that, unlike the mean, higher-order statistical moments of L depend on the opacity of the medium: if σ is the mean extinction coefficient, then $\langle L^q \rangle \propto \langle L \rangle / \sigma^{q-1}$, $q = 1,2,3,\cdots$, as $\sigma \to \infty$ (i.e., RT diffusion limit). The cloud remote sensing implication is that knowledge of both $\langle L \rangle$ and $\mathrm{Var}[L]$ for in-cloud pathlength L can be used to infer both the bulk size and mean opacity of the cloud;. In plane-parallel cloud geometry, that translates to both CGT H and COT $\tau = \sigma H$, irrespective of the value of the latter. In other words, we are no longer limited to the range of COT where there is enough sensitivity in (continuum) reflected radiance to distinguish a change in COT from a fluctuation in the noise, i.e., up to a few 10s.[4] Moreover, while the use of reflected radiance calls for absolute radiometric calibration, inference of moments of L, being based on DO_2AS, only requires a relative calibration across spectral channels.

Figure 1 is adapted from a forthcoming paper by Davis et al. (2021) where a new derivation of the invariance law for $\langle L \rangle$ is presented along with a specific prediction for $\mathrm{Var}[L](\tau)$ in the diffusion limit for plane-parallel geometry. Numerical validation of the diffusion-theoretical predictions for $\langle L \rangle$ and $\mathrm{Var}[L](\tau)$ is performed. **Figure 1** shows both moments as a function of τ for both isotropic and Henyey and Greenstein (1941) phase functions, assuming that asymmetry factor $g = 0.85$ in the latter case. As anticipated, the agreement is exact for $\langle L \rangle$ across all COTs, and the diffusion-based prediction for $\mathrm{Var}[L](\tau)$ becomes excellent as the *scaled* COT $\tau_t = (1 - g)\tau$ exceeds ~4 ($\tau \gtrsim 25$). At any rate, given $\langle L \rangle$ and $\mathrm{Var}[L](\tau)$, one can infer H and τ at any value above ~ $1/(1 - g)$, which is precisely when cloud reflectivity in the continuum starts to loose sensitivity to τ.

In-cloud pathlength L is a random variable, and its moments are emerging here as key intermediate quantities in DO_2AS that can be inferred from spectroscopic data at sufficiently high resolution (Davis et al., 2021). **Figure 1** indeed shows that, given $\langle L \rangle(H)$ and $\mathrm{Var}[L](H, (1 - g)\tau)$, we can infer H and τ, knowing that g hardly deviates from 0.85 in liquid clouds. MUltiple Scattering Cloud Lidar (MUSCL) (Davis et al., 1999a; Davis A. B. et al., 1999b; Davis et al., 2009) is another emerging technology in cloud remote sensing from above or below (Cahalan et al., 2005; Polonsky et al., 2005; Davis, 2008) where the whole distribution of in-cloud pathlengths is measured directly. This is done by temporal binning the return times (i.e., L/c) of photons injected into a cloud using a pulsed laser beam. Now, the signal in each time bin can be noisy, but the statistical moments $\langle L \rangle$ and $\mathrm{Var}[L]$ are robust. As different as are their instrumental implementations, it is clear that DOxAs and MUSCL share the same fundamental signal physics grounded in time-dependent RT. Interestingly, DO_2AS is an inherently daytime observation while MUSCL operates strictly at nighttime since the steady sunlight diffusely reflected or transmitted by the cloud would overwhelm the laser light in every time-bin (Davis, 2008). DO_2AS and MUSCL are therefore the ideal pair of instruments for a satellite mission for pathlength-based cloud observation that would deliver CTH, CGT, COT and possibly a measure of internal variability from turbulence (Davis et al., 2009).

[4]Indeed, an opaque cloud's reflectivity $R(\tau)$ can be approximated by $1/(1 + 2\chi/(1 - g)\tau)$, with $\chi = 2/3$. Maximum sensitivity to τ on a %-scale is realized when $(\mathrm{d}/\mathrm{d}\log\ \tau)^2\ R = 0$, which occurs in the above diffusion approximation at $\tau = 2\chi/(1 - g) \approx 9$ for the canonical value of $g = 0.85$ for liquid clouds.

4 SUMMARY AND DISCUSSION

In this PERSPECTIVE article, we above all celebrate space-based remote sensing using O_2 absorption to track clouds in the vertical dimension above every pixel. To that effect, we survey the relevant literature emphasizing theory up to 2010, which is roughly when there were enough space assets delivering O_2 A-band observations of clouds to see the research become predominantly data-driven. We hope to see others write the important literature review about post-2010 studies of clouds from space-borne O_2 absorption observations. Another worthwhile review would focus on ground-based cloud studies with O_2 absorption spectroscopy, and yet another should focus on using O_2 absorption spectroscopy from above or below to locate aerosol layers in the vertical dimension.

Building on our limited-scope literature survey, we support the viewpoint that EPIC/DSCOVR has been a pathfinder in O_2 absorption-based cloud remote sensing. Several other satellites carry sensors with O_2 absorption capability, EPIC however has by far the largest standoff distance and is also unique in its spectral sampling strategy: "in-band" and "continuum" pairs of channels each for the A- and B-bands. Another hallmark of EPIC's use of O_2 absorption to probe clouds is the impetus it has generated for progress in the associated remote sensing science that is centered on the concept of pathlength cumulated by sunlight, from source to sensor, between every scattering event along the way. To substantiate this claim, we revisited three papers in the *Journal of Quantitative Spectroscopy and Radiative Transfer* that directly address EPIC's characterization of clouds using O_2 absorption, and previewed a key result from a forthcoming one.

Determination of cloud structure in the third dimension is a goal shared by O_2 absorption spectroscopy and other emerging techniques in cloud remote sensing, for instance, 3D computational cloud tomography (CCT). CCT has, so far, been demonstrated on data with small pixel scales that are readily achievable with airborne multi-view sensors, whether imaging (Levis et al., 2015; Levis et al., 2017; Levis et al., 2020; Levis et al., 2021) or not (Alexandrov et al., 2021). When dealing with such fine pixels, in the 10s of meters, there are necessarily significant radiative fluxes crossing pixel boundaries, thus requiring 3D RT forward modeling. There has been recent progress toward 3D CCT from space using moderate (~100s of meters) resolution multi-angle data from the likes of MODIS and MISR/Terra. On top of the 3D RT effects, this effort has to deal with complications from the larger pixels (optically thick, potentially with high internal heterogeneity) and accordingly larger clouds (Forster et al., 2021).

Looking ahead, we know that O_2 absorption observation is typically implemented in spectroscopy, and the more channels in the absorption band the better since the diversity in absorption coefficient ensures probing different depths into the cloud. However, this key ability can also be obtained using a single absorption channel, as for either of EPIC's O_2 absorption bands, in a multi-view angle collection. POLDER (2004–2013) pioneered the multi-view O_2 absorption observation strategy, and that path will be followed in short order by MAIA, SPEXone/PACE and 3MI. Spectroscopy-based O_2 absorption is also heading into a bright future, starting with OCI/PACE and NASA's upcoming Atmospheric Observing System (AOS). Someday, we may see the deployment of DSCOVR follow-on missions at Lagrange-1 and Lagrange-2 (Valero et al., 2021). At any rate, it will be interesting to see how future synergistic retrievals will blend O_2 absorption spectroscopy with other passive sensing modalities, such as multi-view imaging and CCT, thus enabling robust 3D cloud property retrievals on a global scale.

DATA AVAILABILITY STATEMENT

Inquiries about data used in **Figure 1** can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

AD proposed and wrote this article for the Special Issue on "DSCOVR EPIC/NISTAR: Five Years of Observing Earth from the First Lagrangian Point." YY is the DSCOVR Science Team PI responsible for operational EPIC cloud products, including cloud heights from O_2 A- and B-band channels; AM is Deputy Project Scientist for the DSCOVR mission. They both provided substantive feedback on the manuscript.

FUNDING

YY acknowledges sustained funding from the DSCOVR Science Team program. AD is supported by NASA's SMD/ESD DSCOVR mission (EPIC CLOUD ALGORITHMS, Project: 105357, Task: 239702.04.32.01.13, HQs PM Richard S. Eckman). This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004).

ACKNOWLEDGMENTS

We thank Mark Richardson, Quentin Libois, Nicolas Ferlay, Qilong Min, Jay Hermann, Dennis O'Brien, and Andy Sayer for many fruitful discussions about the science and history of probing clouds from space with DO_2AS techniques.

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