Direct Detection Doppler Lidar Technology and Techniques

Technology Assessment Studies in support of GTWS

By the
TAT Direct Detection subcommittee members:

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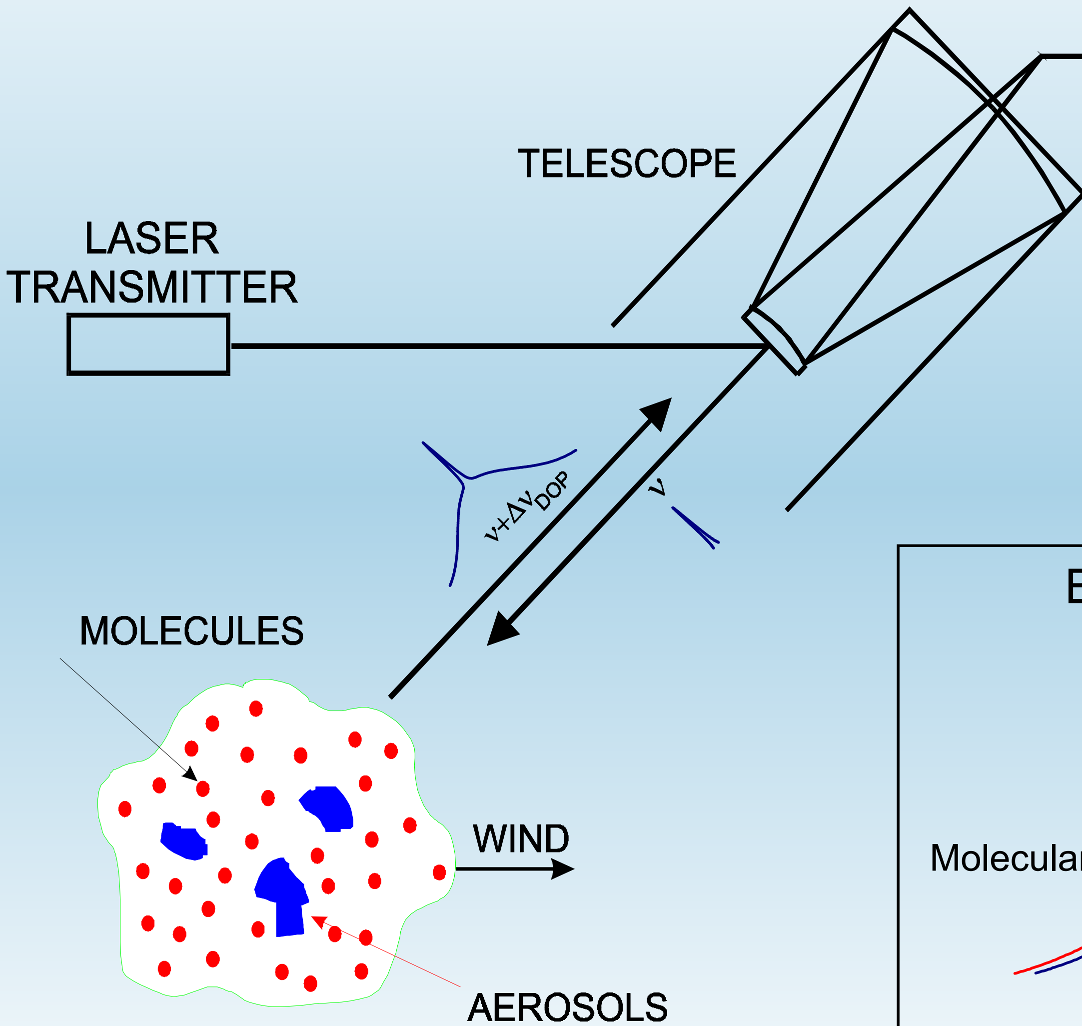
Introduction

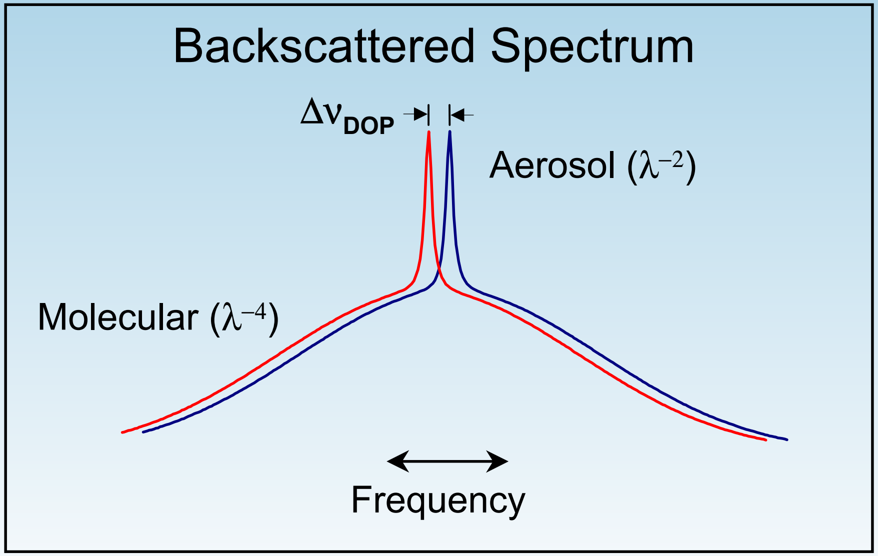
- **Technology assessment studies initiated to assess ‘do-ability’ of GTWS draft requirements.**
    - **Establish performance baseline and scaling relationships**
    - **Evaluate technology tallpoles**
- **Included evaluation of Direct Detection Doppler Lidar approaches proposed for space**
    - Fringe imaging
    - Double edge technique
- **Fidelity of the designs top level to allow inclusion of new technologies, approaches**
- **Provide input to GTWS DDDL end-to-end instrument and mission design studies (see Ken Miller’s talk tommorrow)**

Doppler Lidar Measurement Concept



DOPPLER RECEIVER -
Multiple flavors - Choice drives science/technology trades

- Coherent 'heterodyne' (e.g. SPARCLE/MSFC)
- Direct detection "Double Edge" (e.g. Zephyr/GSFC)
- Direct detection "Fringe Imaging" (e.g. Michigan Aerospace)



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Direct Detection Doppler Lidar

- Measured signal is proportional to intensity
- High resolution optical filter used to measure Doppler shift
- Draws on technology used with other space lidars (MOLA, GLAS, VCL, Picasso)
    - Well developed solid state lasers
    - Large aperture ‘light bucket ‘ telescopes
    - Photon counting detectors
- Shot averaging to increase S/N
- Utilizes aerosol or molecular backscatter
    - Molecular provides clear air winds in free troposphere/over oceans
- 2 primary implementations ‘Double Edge’ and ‘Fringe Imaging’

Direct Detection Wind Lidar Key Technologies

- High spectral resolution all solid state laser transmitter
  - Well developed diode-pumped Nd:YAG technology for small, efficient, long-life, space qualified laser
- High spectral resolution optical filters
  - High resolution, high throughput, stable, tunable optical filters for Doppler wind measurement
- Photon counting detectors and arrays at 355 nm and 1064 nm
  - Low noise, high quantum efficiency detectors suitable for space applications
- Novel large aperture scanning lidar receivers
  - Large aperture, ‘light bucket’ telescope technologies (deployables, membrane optics)
  - Holographic optical elements provide low mass, simplified scanning, high efficiency at specific wavelength, narrowband filtering

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DDDL Point design ground rules

- Consider both types of direct detection receivers, double edge and fringe imaging, optimized for aerosol and/or molecular backscatter.
- Use lidar model of McGill et al* as baseline. Cross check with other models (SWA and Gentry) to verify.
- Use Emmitt atmospheric models, including background and enhanced aerosol modes, to generate backscatter and attenuation profiles- NO CLOUDS.
- Fix instrument and spacecraft parameters and vary total laser energy delivered to the TSV to achieve velocity accuracy called out in science requirements at <u>all</u> range gates in the measurement range for a single LOS.
- Total energy is function of laser pulse energy and rep rate and related to average power via the integration time per LOS perspective.
- Max integration time is determined by max horizontal sample (100 km/7.5 km/s =13.33 sec) or by dwell time determined by number of LOS perspectives required (e.g. 4 LOS → 11 sec; 8 LOS → 5 sec).
- Performance trades can then be estimated by scaling using lidar equation

***McGill, M.J. ,W.D. Hart, J.A. McKay, and J.D. Spinhirne (1999), "Modeling the performance of direct-detection Doppler lidar systems including cloud and solar background variability,", *Applied Optics*, 38, 6388-6397.**

Direct Detection Doppler Lidar Signal

1. $$\text{Signal} = \frac{N_S\, E A \eta \tau_{opt}\, \tau_{atm}^2(\lambda)\, [\beta_a(\lambda) + \beta_m(\lambda)]\, \Delta R}{h\nu R^2}$$

2. $S/N \propto \sqrt{\text{Signal}}$

3. $\delta v \propto (S/N)^{-1}$

N_S= number of laser shots
A= telescope area
E= laser pulse energy
η= detection efficiency
τ_{opt}= optical efficiency
$h\nu$= photon energy

$\tau_{atm}(\lambda)$=1 way atmos transmission
$\beta_a(\lambda)$= aerosol backscatter
$\beta_m(\lambda)$=molecular backscatter
R= range to sample volume
ΔR= range resolution

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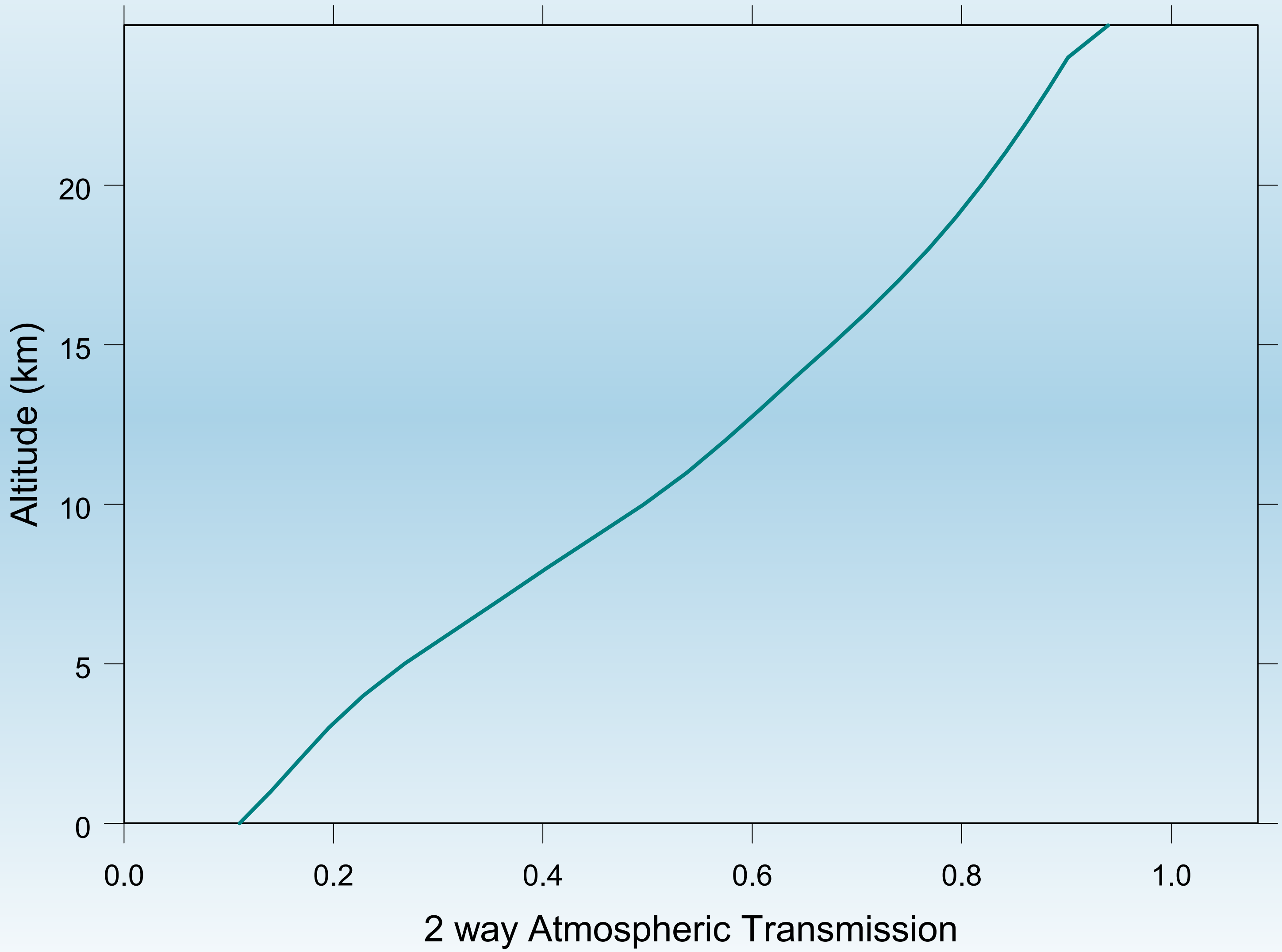
Two way transmission through the atmosphere
45 deg zenith angle



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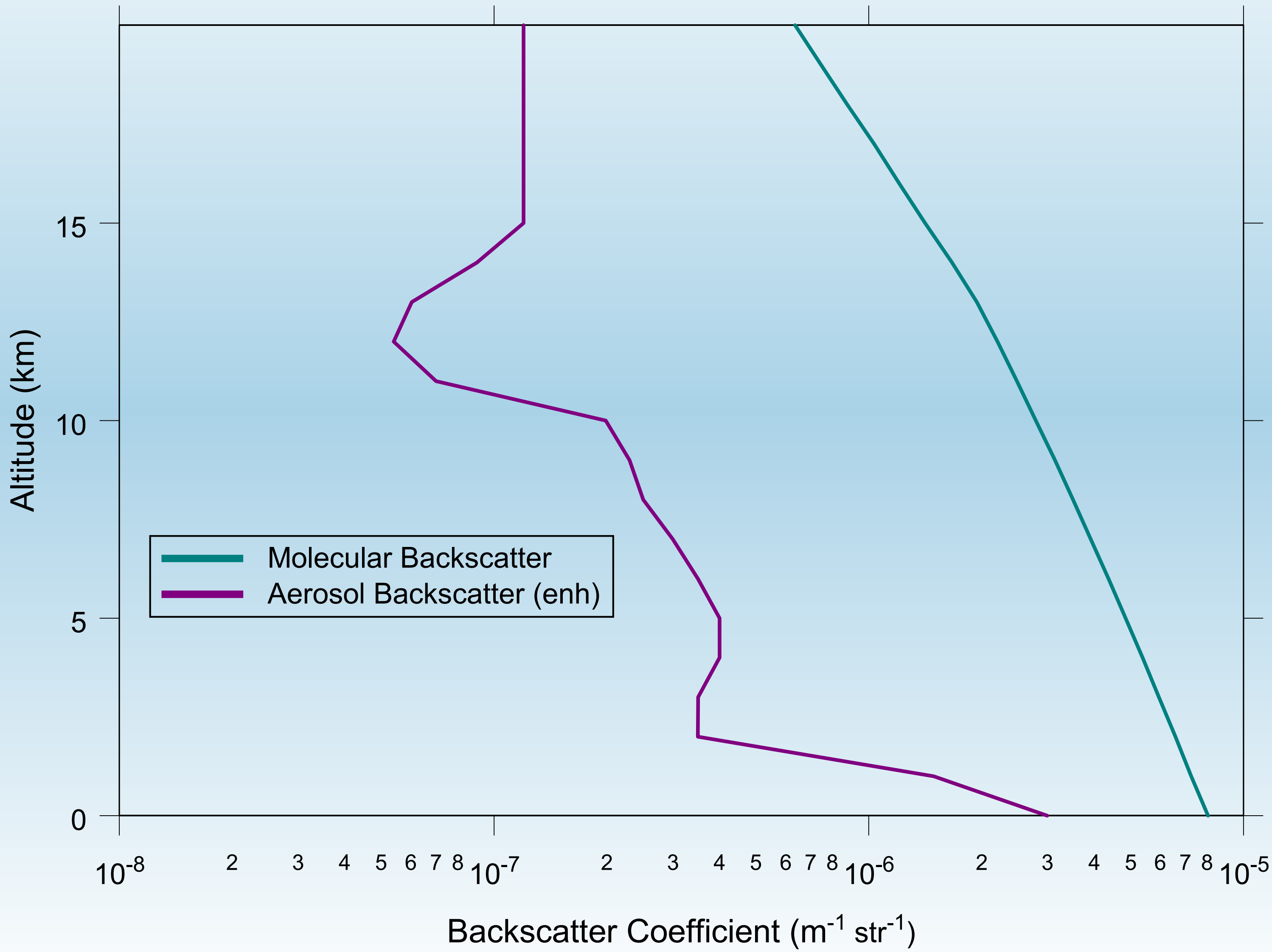
Atmospheric backscatter at 355 nm



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Parameters assumed constant in point design study

PARAMETER	VALUE
molecular 1/e-width at 355 nm ($\Delta\lambda M$)	9.67x10-4 nm (2.30 GHz)
Satellite altitude	400 km
Zenith angle (ϕ)	45 degrees
scan pattern	8 L-O-S
Telescope collecting area	1.227 m^2
Telescope field of view (full angle)	200 μrad
Vertical resolution	1 km from 3-20 km 0.5 km from 0-3 km
Max allowed wind error without (with) turbulence- LOS-P	3 m/s (2.91) from 3-20 km 2 m/s (1.73) from 0-3 km

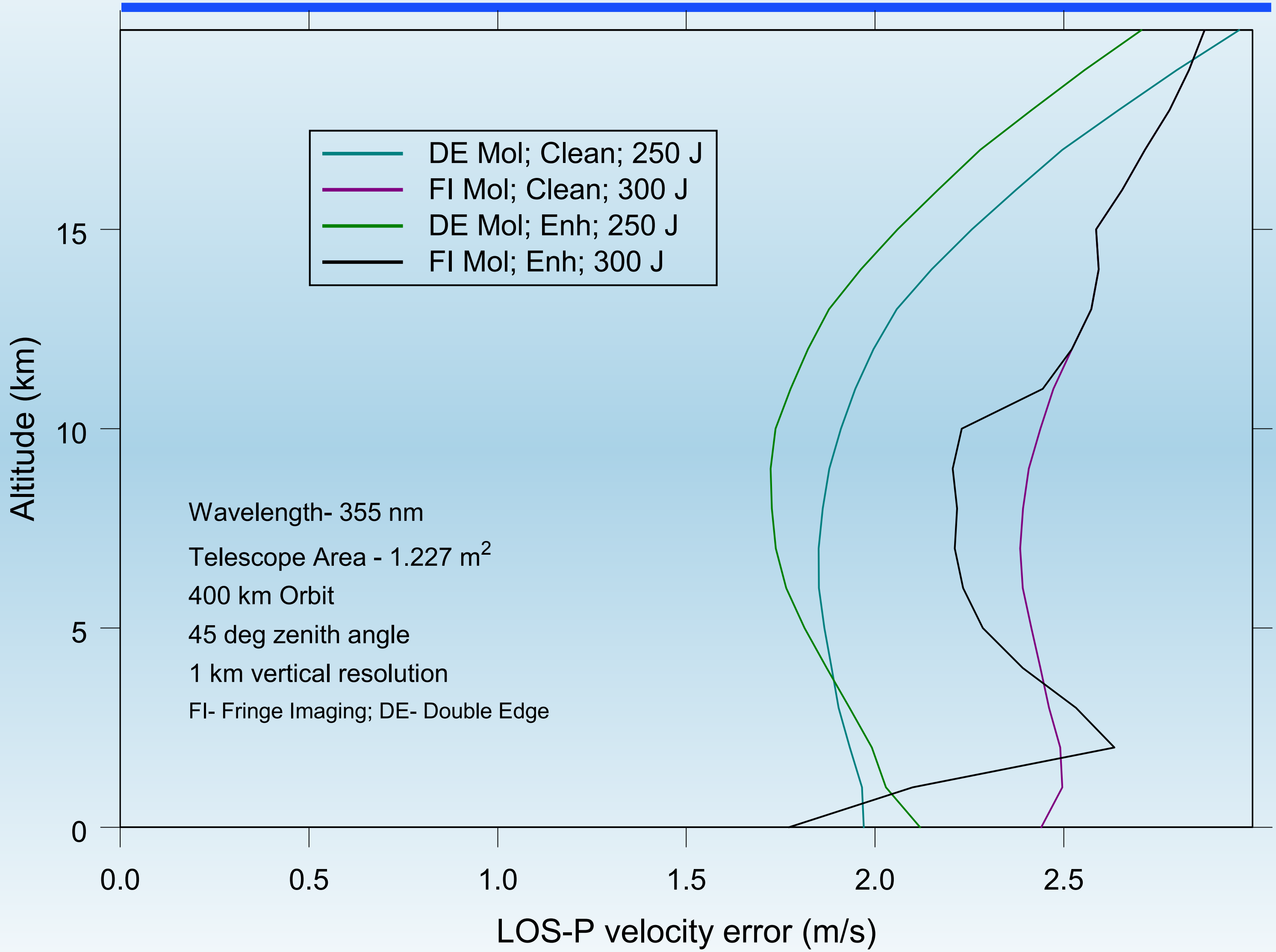
Parameters for FI and DEDG aerosol receivers

	DEDG SYSTEM	FI SYSTEM
wavelength (nm)	1064	355
laser 1/e-width (ΔλL)	1.51x10-4 nm (40.0 MHz)	2.10x10-6 nm (4.99 MHz)
HRE spacing (d)	5.72 cm	30.0 cm
HRE plate reflectivity (R)	93%	88%
HRE reflective finesse (FR)	43.28	24.56
HRE etalon defect (ΔdD)	2.0 nm	2.0 nm
HRE defect finesse	113.2	37.7
HRE aperture finesse (FA)	43.28	29.09
HRE effective finesse (FEFF)	27.44	16.80
loss per plate (L)	0.2%	0.2%
HRE free spectral range (ΔλFSR)	9.89x10-3 nm (2.62 GHz)	2.10x10-4 nm (500 MHz)
optical efficiency (T_O) (includes DF, but not etalons)	34%	34%
filter efficiency (LRE, MRE, absorbers)	74%	74%
overall optical efficiency (T_O)	25.2%	25.2%
integrated solar bandpass (F_W)	xxx pm	xxx pm
detector channels (nC)	------	32
# orders imaged	------	1.1
offset in etalon HWHH	1.00 (47.76 MHz)	-----
beamsplitter efficiency (T_{BS})	45%	-----
detector efficiency (QE)	4%	40%

Parameters for FI and DEDG molecular receivers

	DEDG SYSTEM	FI SYSTEM
wavelength (nm)	355	355
laser 1/e-width (ΔλL)	2.25x10-5 nm (53.6 MHz)	2.25x10-5 nm (53.6 MHz)
HRE spacing (d)	1.25 cm	1.8 cm
HRE plate reflectivity (R)	75.2%	66%
HRE reflective finesse (FR)	10.98	7.51
HRE etalon defect (ΔdD)	3.15 nm	3.15 nm
HRE defect finesse	24	24
HRE aperture finesse (FA)	9.27	32.
HRE effective finesse (FEFF)	6.84	7.20
loss per plate (L)	0.2%	0.2%
HRE free spectral range (ΔλFSR)	5.04x10-3 nm (12.0 GHz)	3.5x10-3 nm (8.33 GHz)
optical efficiency (T_O) (includes DF, but not etalons)	34%	34%
filter efficiency (LRE, MRE, absorbers)	74%	74%
overall optical efficiency (T_O)	25.2%	25.2%
integrated solar bandpass (F_W)	2.66 pm	3.65 pm
detector channels (nC)	------	32
# orders imaged	------	1.
offset in etalon HWHH	3.10 (2.72 GHz)	-----
beamsplitter efficiency (T_{BS})	48%	-----
detector efficiency (QE)	40%	40%

Direct Detection Molecular System Performance



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Summary

- The basic scaling for a molecular direct detection (DD) Doppler lidar is well established and prediction of performance in an idealized atmosphere (no aerosols or clouds) is straight forward.
  - Velocity error scales directly with S/N (i.e. photons detected)
- Performance of an DD aerosol channel is dependent on variability of aerosol backscatter but in all cases studied is of marginal benefit.*
- Using a generic point design for a system at 355 nm it appears the GTWS draft requirements will require a system with a large EAP. Principle drivers include:
  1. Performance in PBL
  2. Requirements for 8 LOS (EAP increases linearly with # of LOS)
  3. Dwell time (horizontal sampling)
- Technology advances will be required to meet future. Emphasis on
  - Lasers
  - Telescope and scanning optics
  - Detectors (high QE, low noise) -single element and arrays

* Further Study Required