Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: [Propagation of THz ps pulses through the atmosphere]
Date Submitted: [1 July, 2019]
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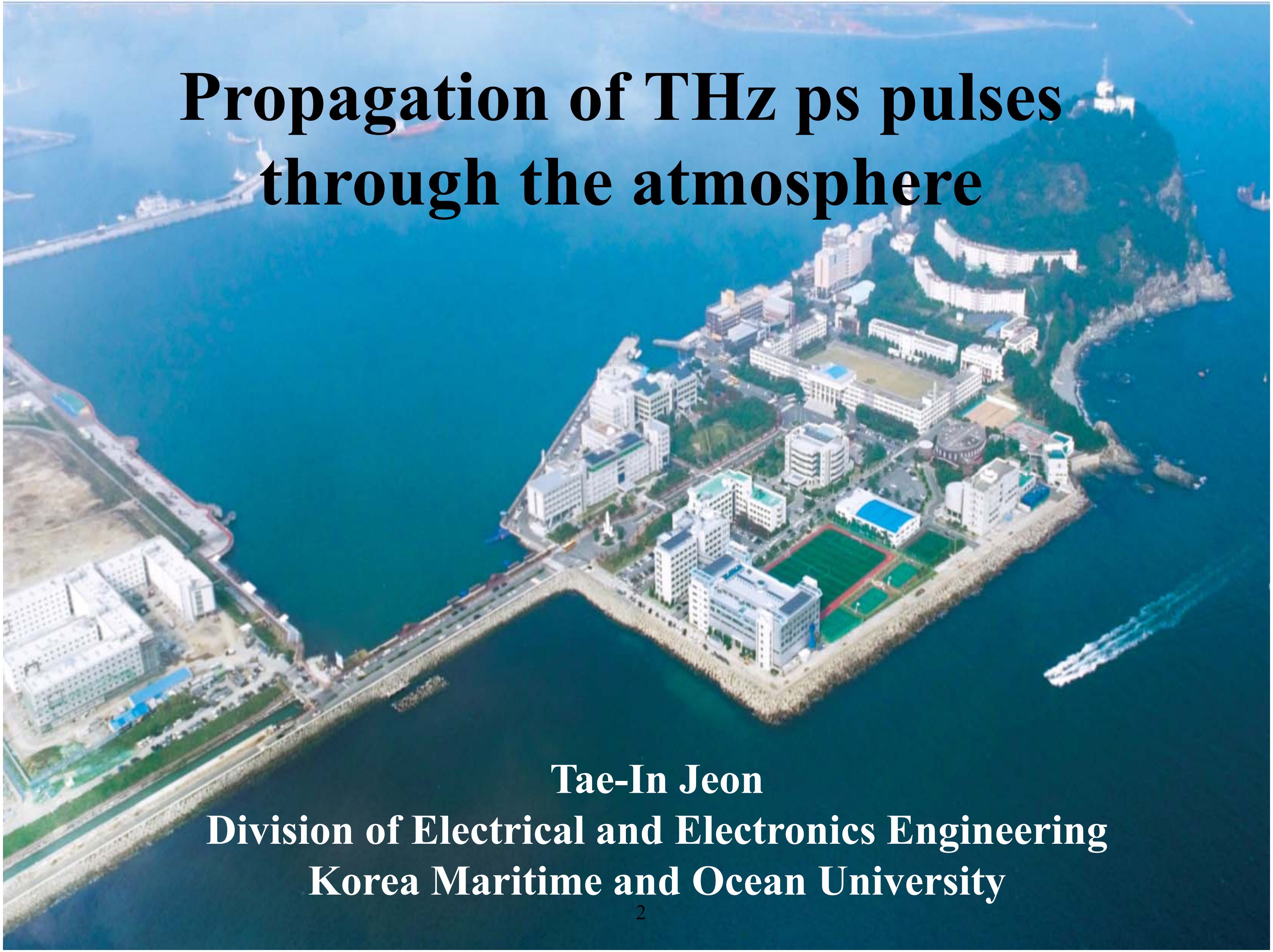
Re: [n/a]
Abstract: [The ps THz pulses propagated 186 and 910 m distances in the atmosphere were measured with 1 and 0.4-THz bandwidth, respectively. The THz pulses well propagated through a 186 m distance with different water vapor density (WVD) and weather conditions such as clouds, rain, and snow. The measured time shift depends on WVD by comparing the 186-m- and 910-m-long path measurement. When the RH and temperature are continuously varied during the measurement, the THz pulses also continuously shifted with 2.36 and 15.53 ps/(g/m3) ratio for a 186- and 910-m propagation, respectively. THz long path water vapor density studies are necessary to evaluate proposed applications in the atmosphere, such as communications and monitoring pollutants and dangerous gases.
Purpose: [Information of the Technical Advisory Group THz]

Propagation of THz ps pulses through the atmosphere



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Outline

- Measurement of THz pulse propagated through a 186 m distance [1]
  - Comparison THz pulses with different weather conditions
- Measurement of THz pulses with a 0.4-THz bandwidth through a 910-m distance [2]
  - Comparison time shift with theory and measurement
  - N_2O gas measurement [3]
- Conclusions

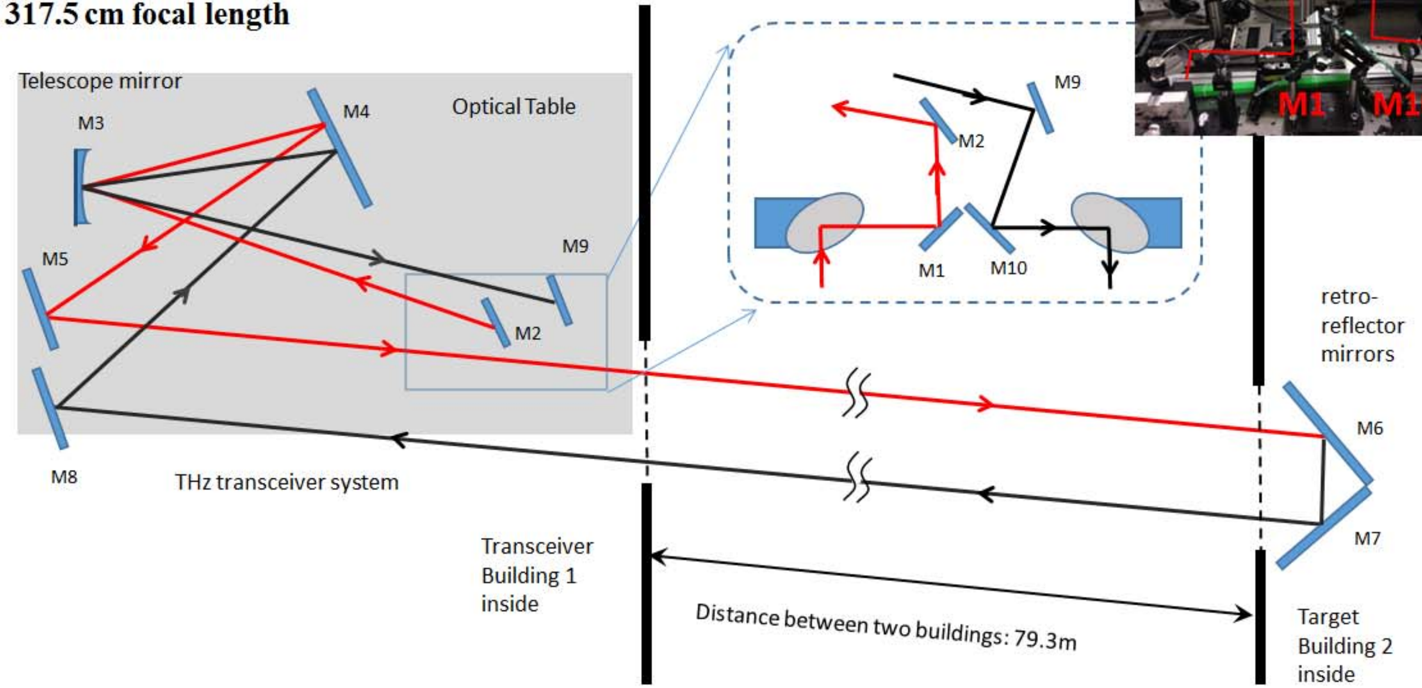
Air traffic control near the airport

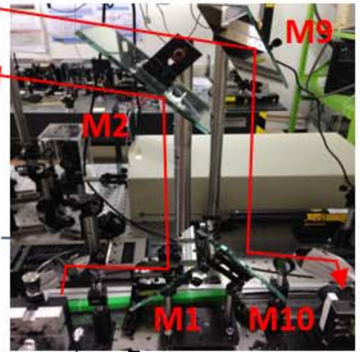
Military short range communication

Wildfire and environmental monitoring

186 m THz transmission setup between two Buildings

Telescope mirror:
30.5 cm dia.
317.5 cm focal length

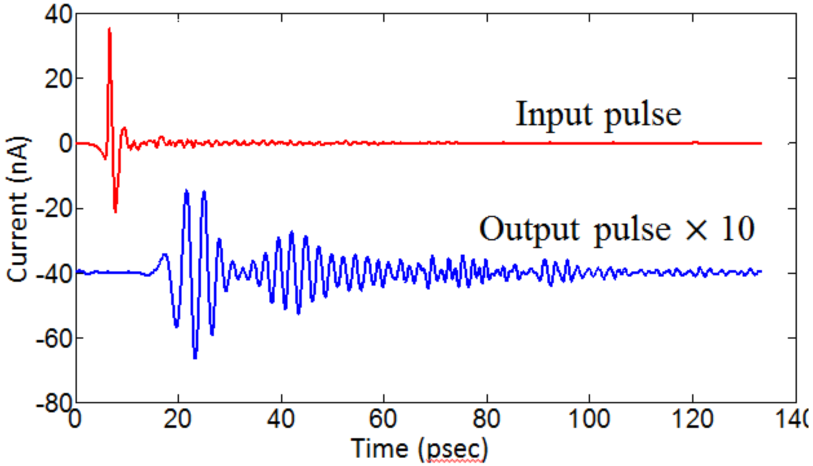


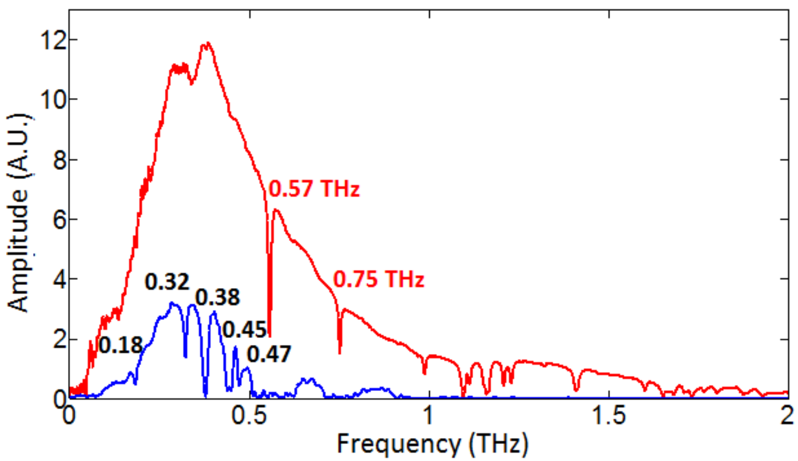


Photograph of transceiver and target building.

- The distance between two buildings is 79.3 m
- The total round trip path between Tx and Rx is 186 m.
- The total outdoor path is 159m
- 84.01 MHz repetition rate & 52nd laser pulse used to detect THz pulse

Comparison input pulse (0.6m) and output pulse (186m)





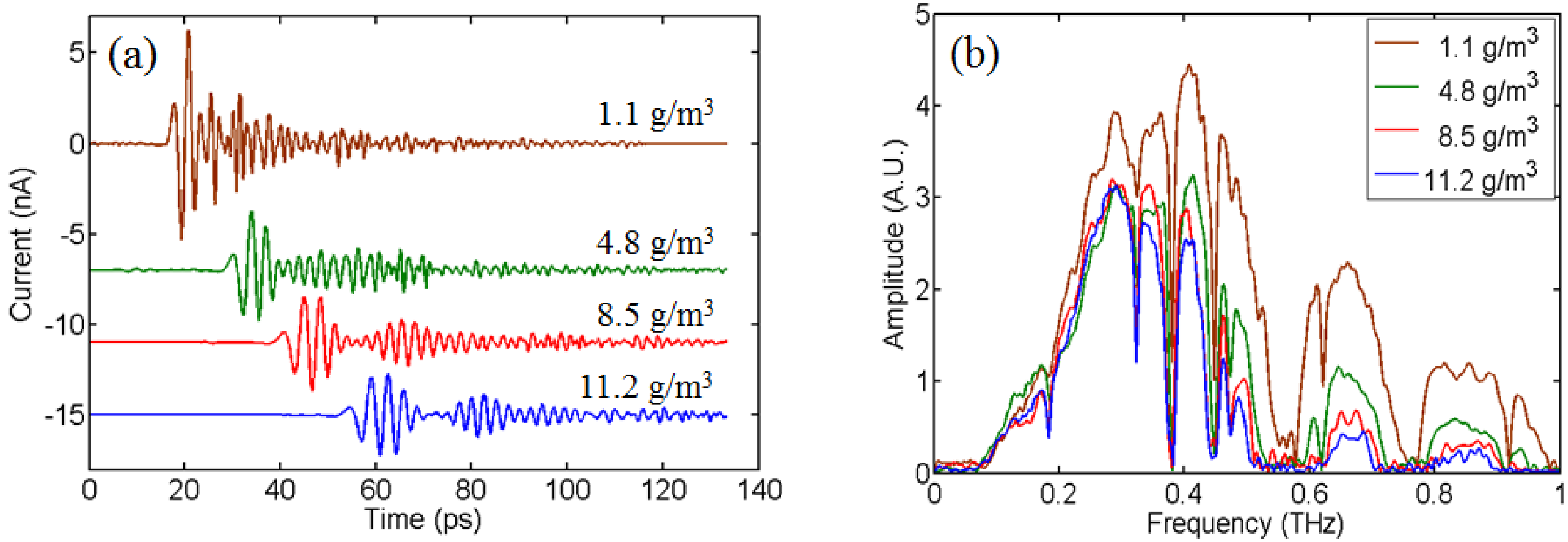
Tx chip : GaAs 10-80-10
Rx : LT-GaAs 10-100-10
(long dipole antenna)

1000 channels (data points) with 20-µm steps between channels

Input pulse:
0.6 m long beam path
RH 28.1%
S/N 15,000:1

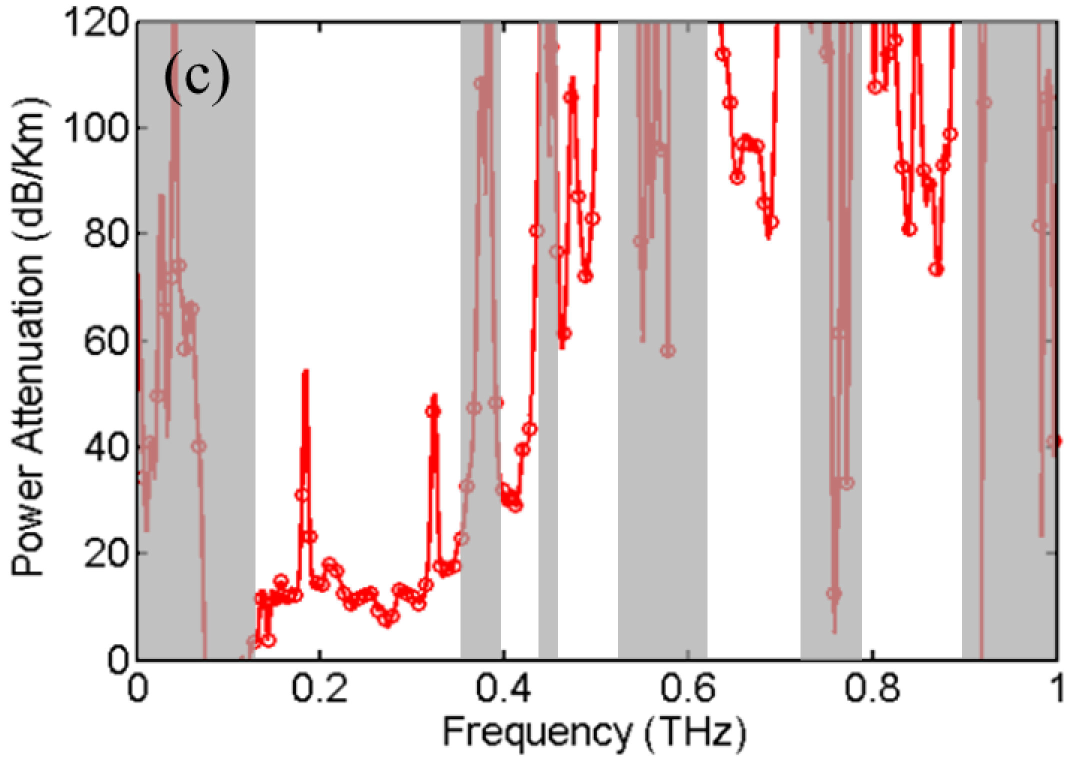
Output pulse:
186 m long beam path
RH 54.0%
S/N 1,400:1

Comparison THz pulses with different relative water vapor density



	Relative Humidity (%)	Temperature (°C)	Water vapor Density (g/m^3)	Wind Velocity (m/s)
	12.5	9.6	1.1	1.3
	37.7	14.8	4.8	1.2
	54.0	18.3	8.5	2.9
	73.9	17.6	11.2	3.1

Power attenuation



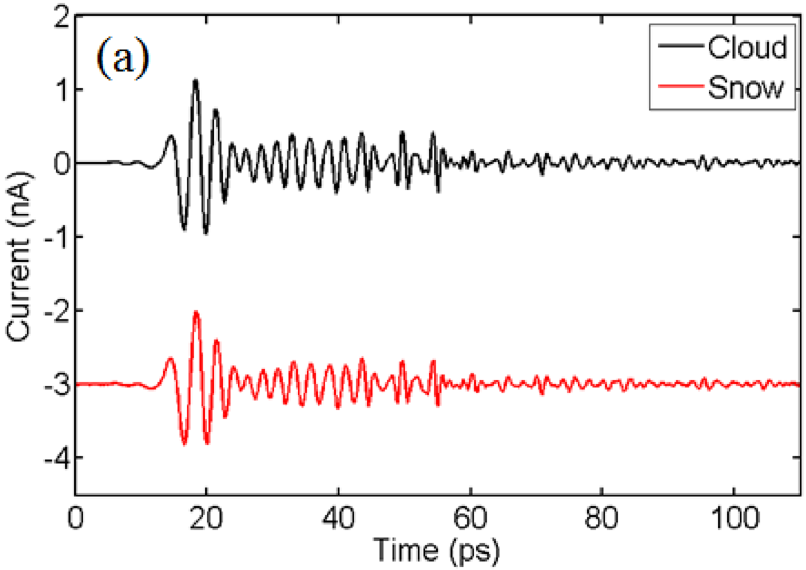
- Measured power attenuation coefficients for the WVD difference of 10.1 g/m, between the reference spectrum of 1.1 g/m and sample spectrum of 11.2 g/m.
- The grey regions cover the no-signal areas caused by the strong water vapor absorption lines.

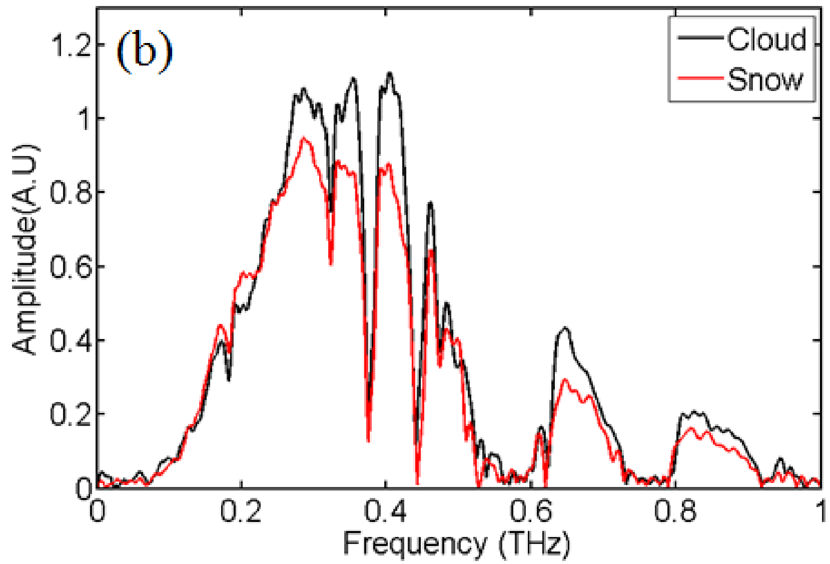
THz propagation in snowing weather

2cm/h snowfall
2mm/h rainfall

	Weather	Relative Humidity (%)	Temperature (ºC)	Water Vapor Density (g/m^3)	Wind Velocity (m/s)
	Cloud	73.4	4.2	4.5	1.9
	Snow	79.4	2.9	4.4	2.6

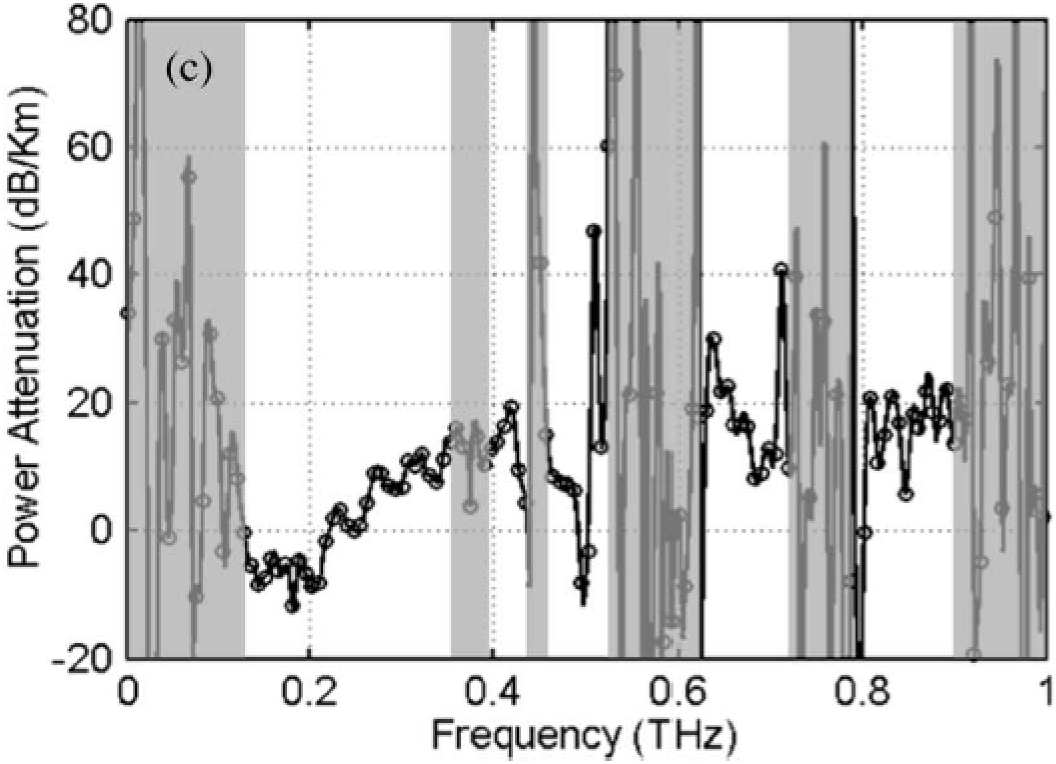
Measured THz pulses in snowing weather





- The cloudy (with snow) sample pulse was measured first, and the cloudy (no snow) reference pulse was measured 40 min later.
- There are relative spectral amplitude fluctuations between the reference and sample spectra in the region of 0.2 THz, for which the snow amplitude exceeds the cloudy amplitude.

Measured power attenuation in snowing weather

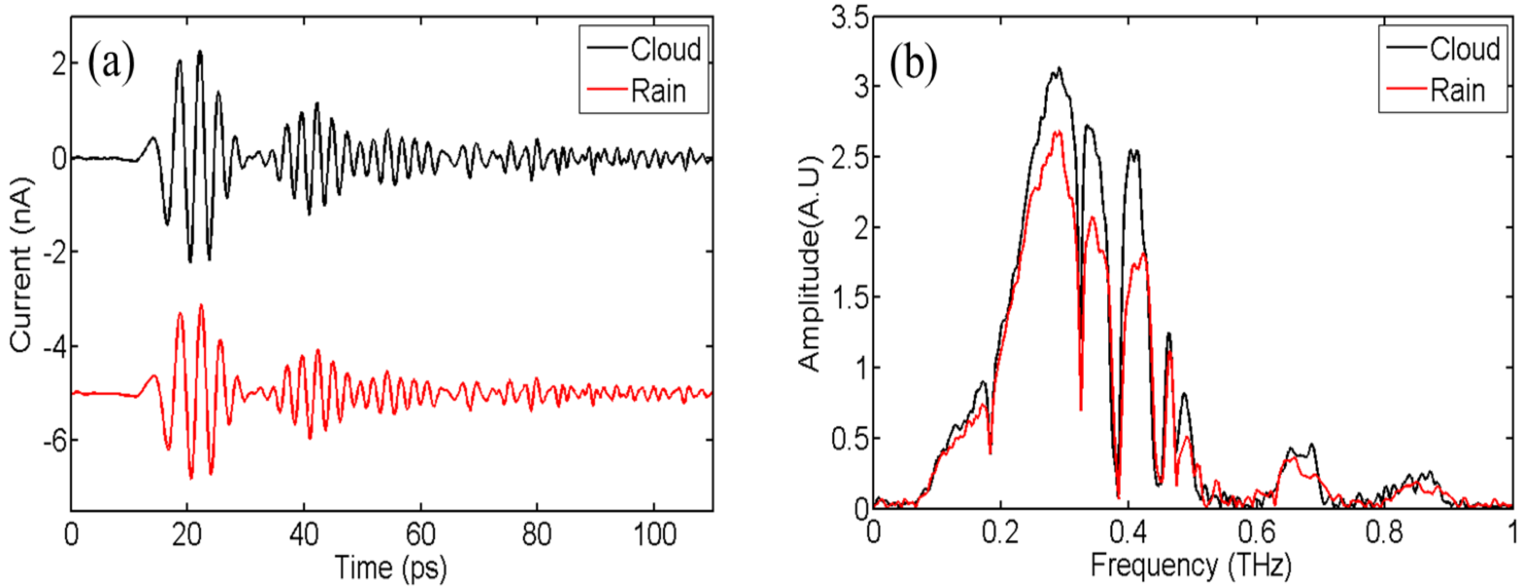


Measured power attenuation coefficients for the reference spectrum of cloudy (no snow) starting at 100 GHz and the output sample spectrum of cloudy (with snow).

THz propagation in raining weather

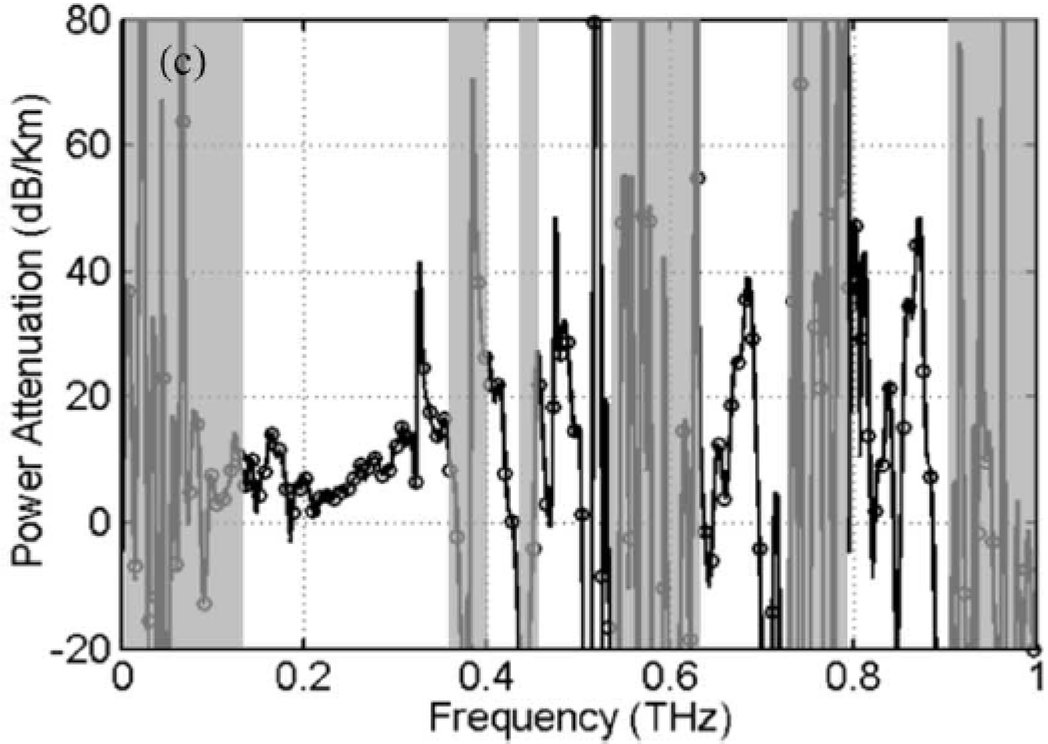
	Weather	Relative Humidity (%)	Temperature (ºC)	Water Vapor Density (g/m³)	Wind Velocity (m/s)
	Cloud	73.9	17.6	11.2	3.1
	Rain	88.7	13.8	10.6	1.1

Measured THz pulses in raining weather



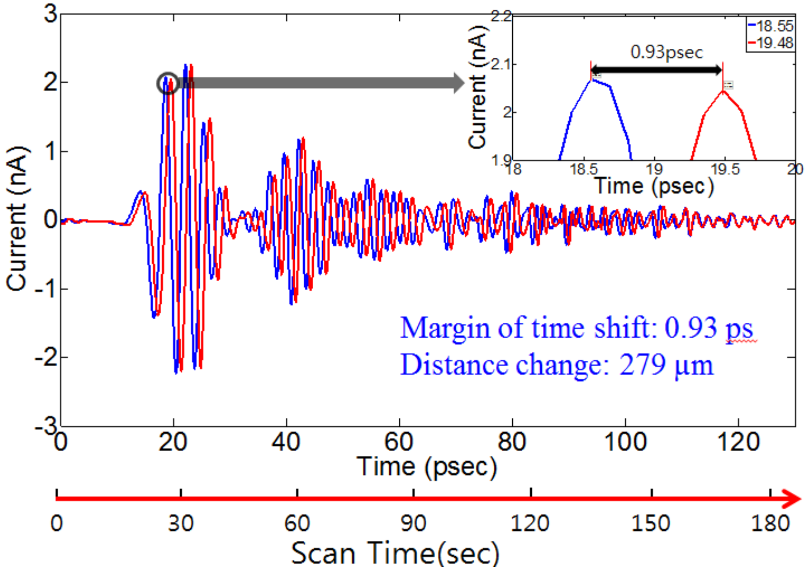
- The cloudy (no rain) references pulse was measured first, and the cloudy (with rain) sample pulse was measured 5 hours later.

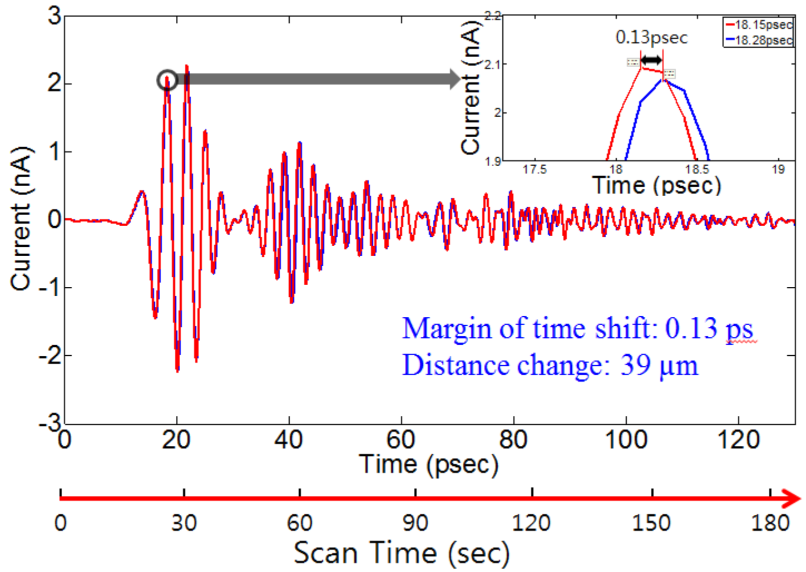
Measured power attenuation in raining weather



Measured power attenuation coefficients for the reference spectrum of cloudy (no rain) starting at 100 GHz and the output sample spectrum of cloudy (with rain).

Compare two THz pulses on windy and calm day

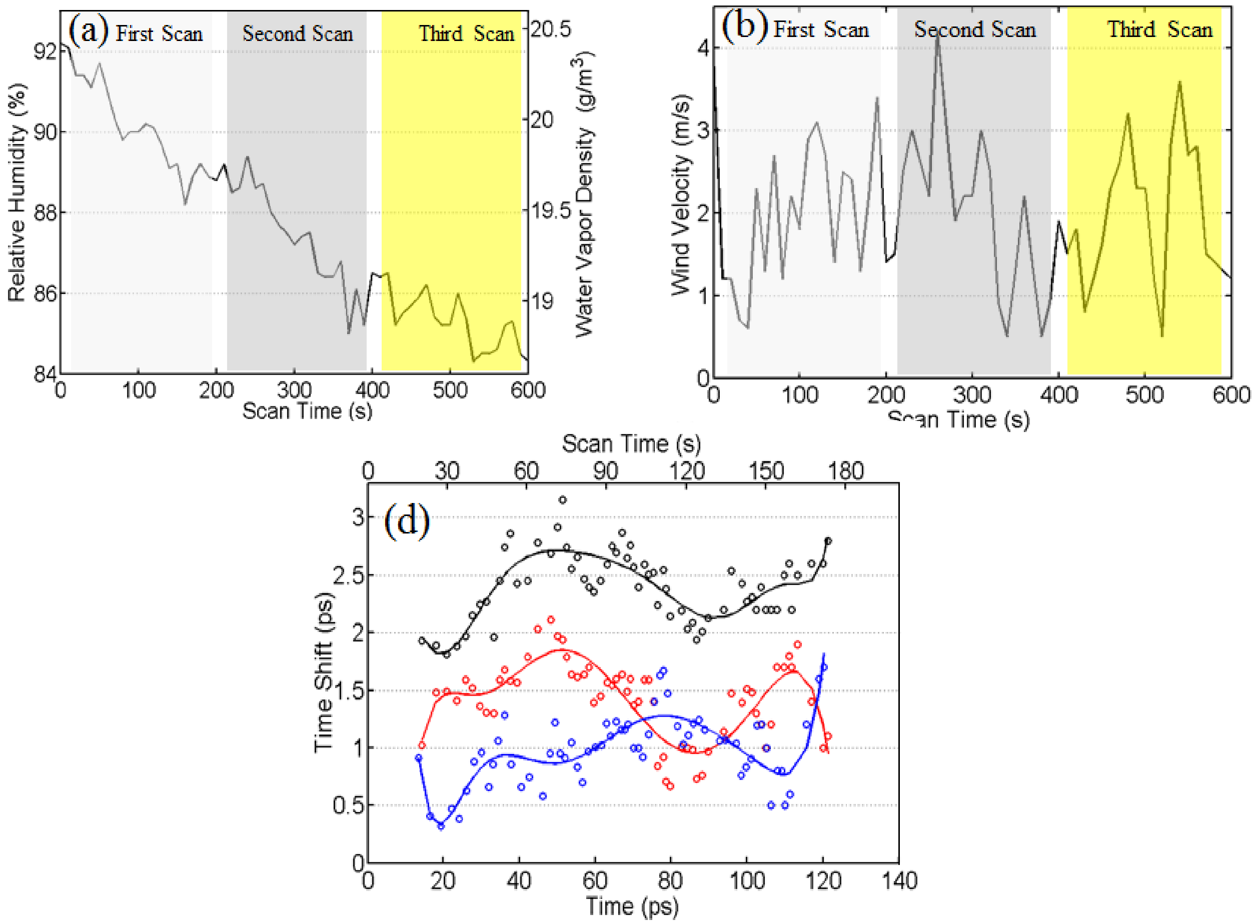




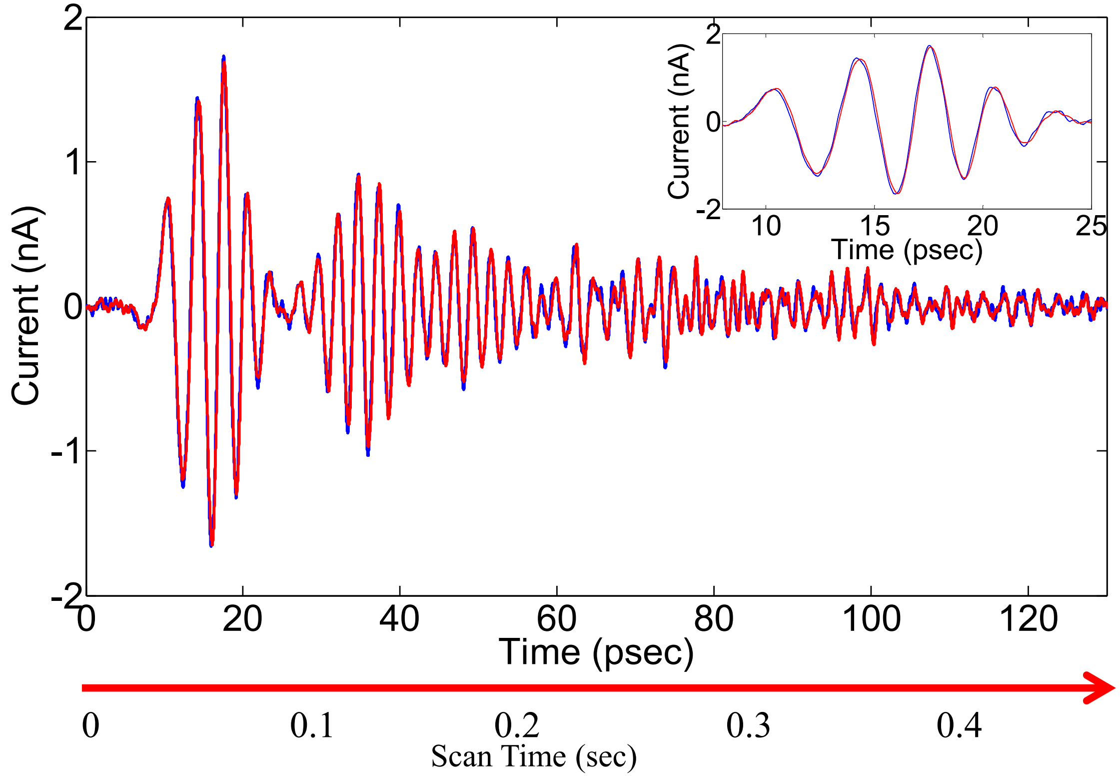
	Temperature	Relative Humidity	Wind velocity
	16.5º	83.1%	3.9 m/s

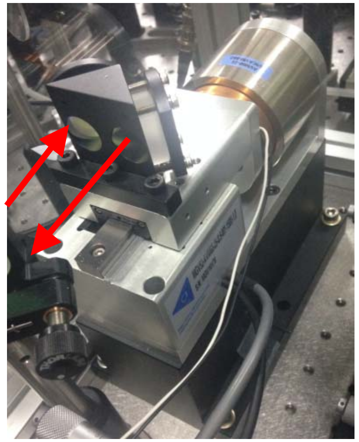
	Temperature	Relative Humidity	Wind velocity
	16.1º	78.8%	1.1 m/s

Measured relative humidity and wind velocity during scans



Fast scan measurement : Comparison Two over-lapped THz pulses

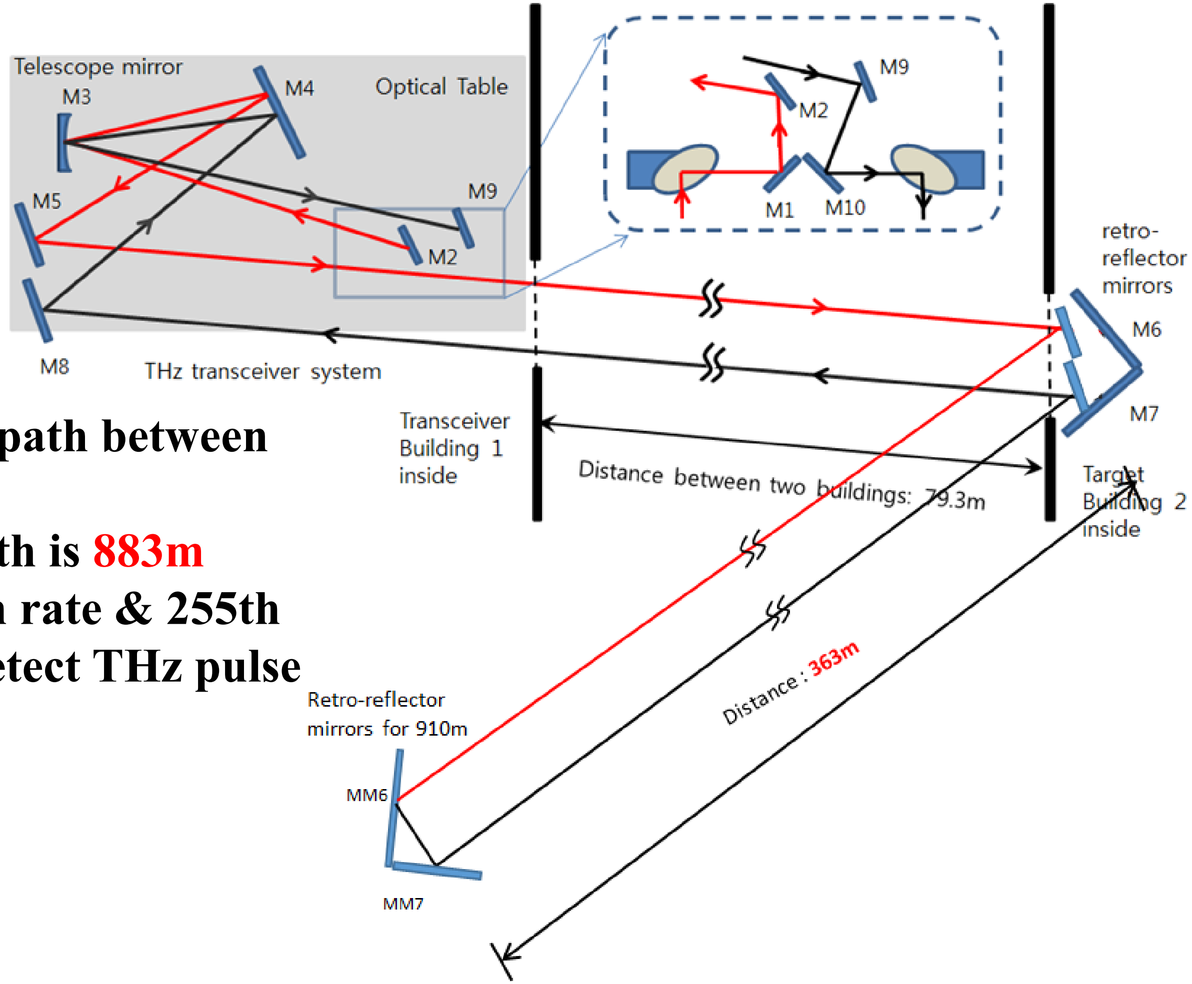




Fast scan (voice coil)

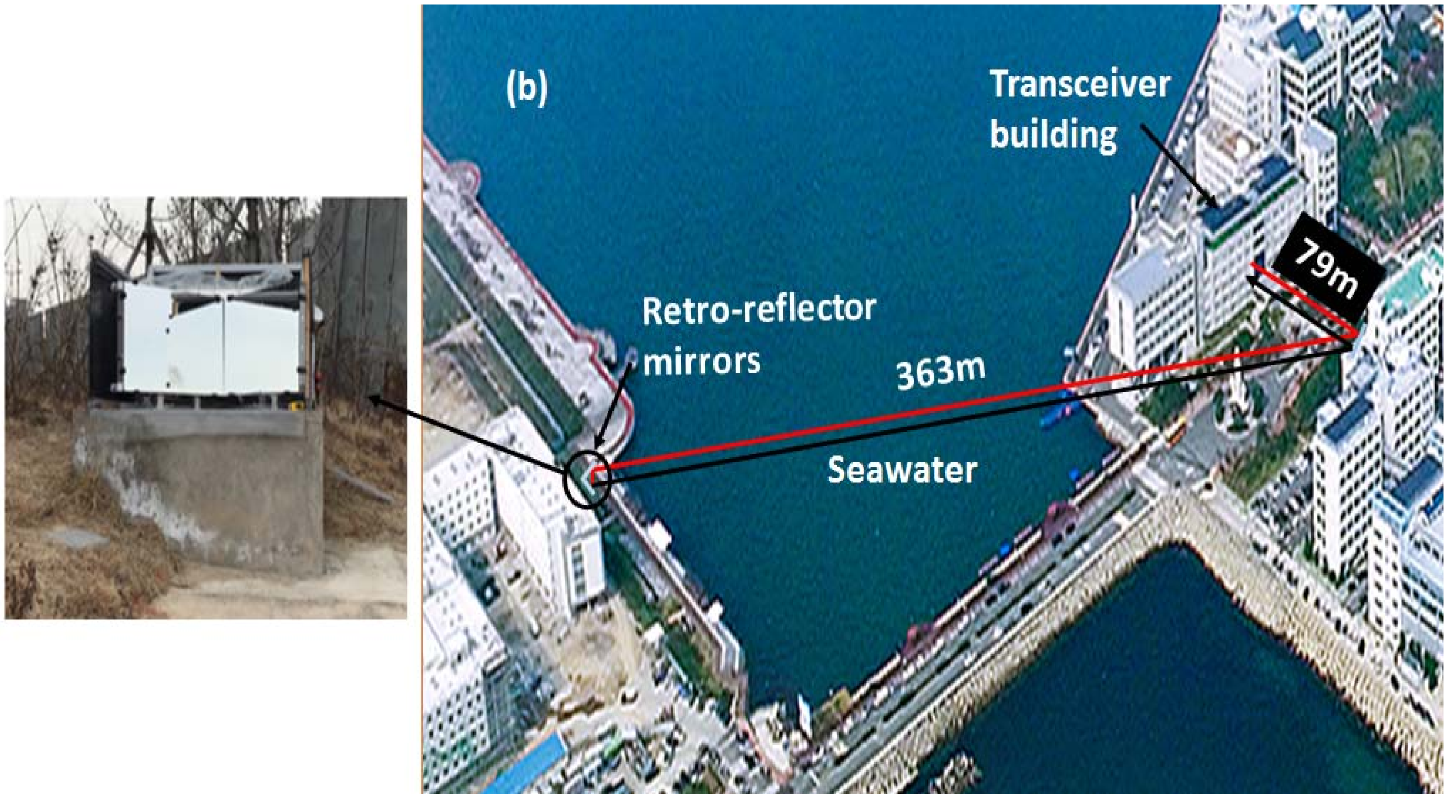
Temperature	Relative Humidity	Wind velocity
13.9º	85.2% RH	2.1 m/s

Long-path (910m) THz setup

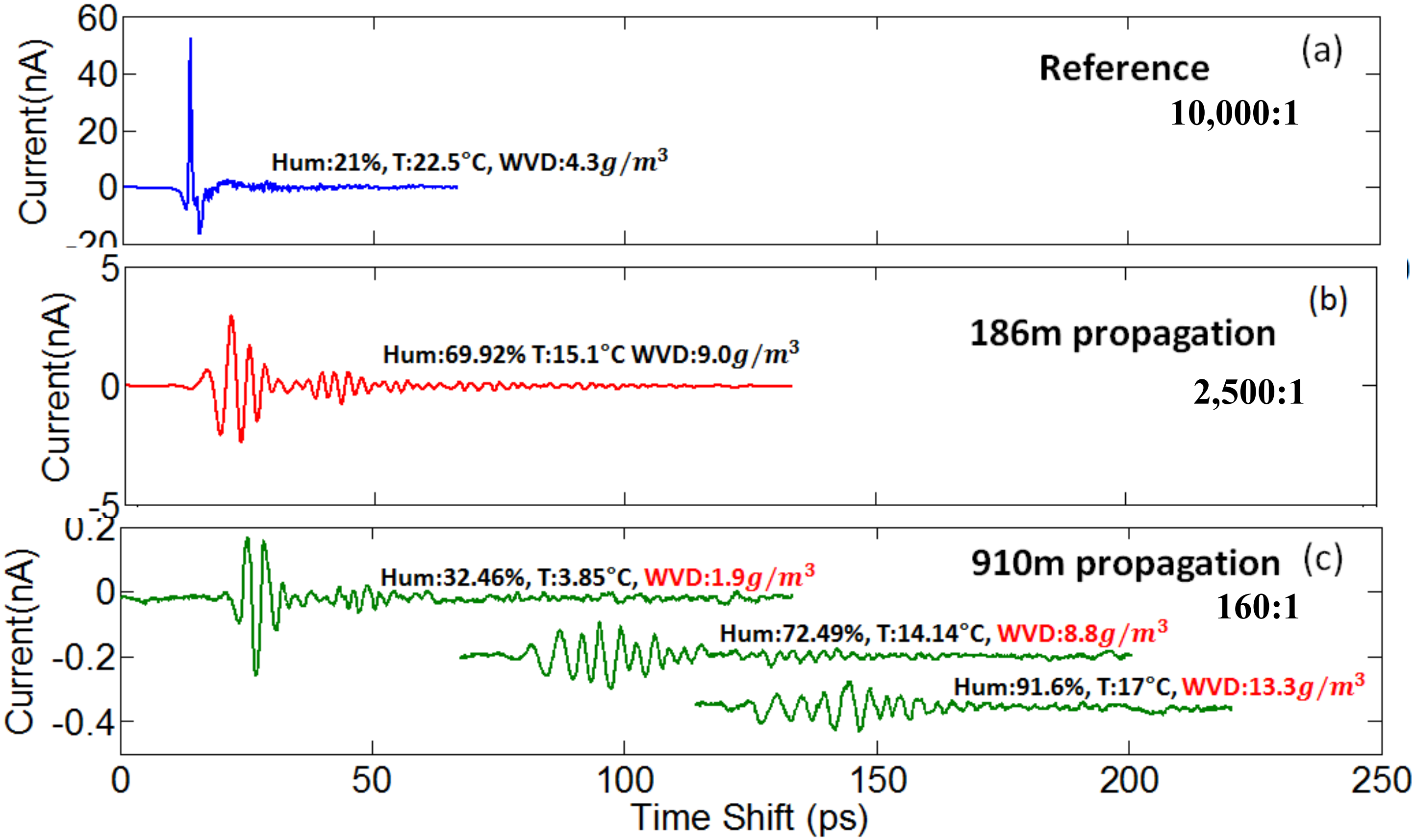


- The total round trip path between Tx and Rx is 910 m.
- The total outdoor path is 883m
- 84.01 MHz repetition rate & 255th laser pulse used to detect THz pulse

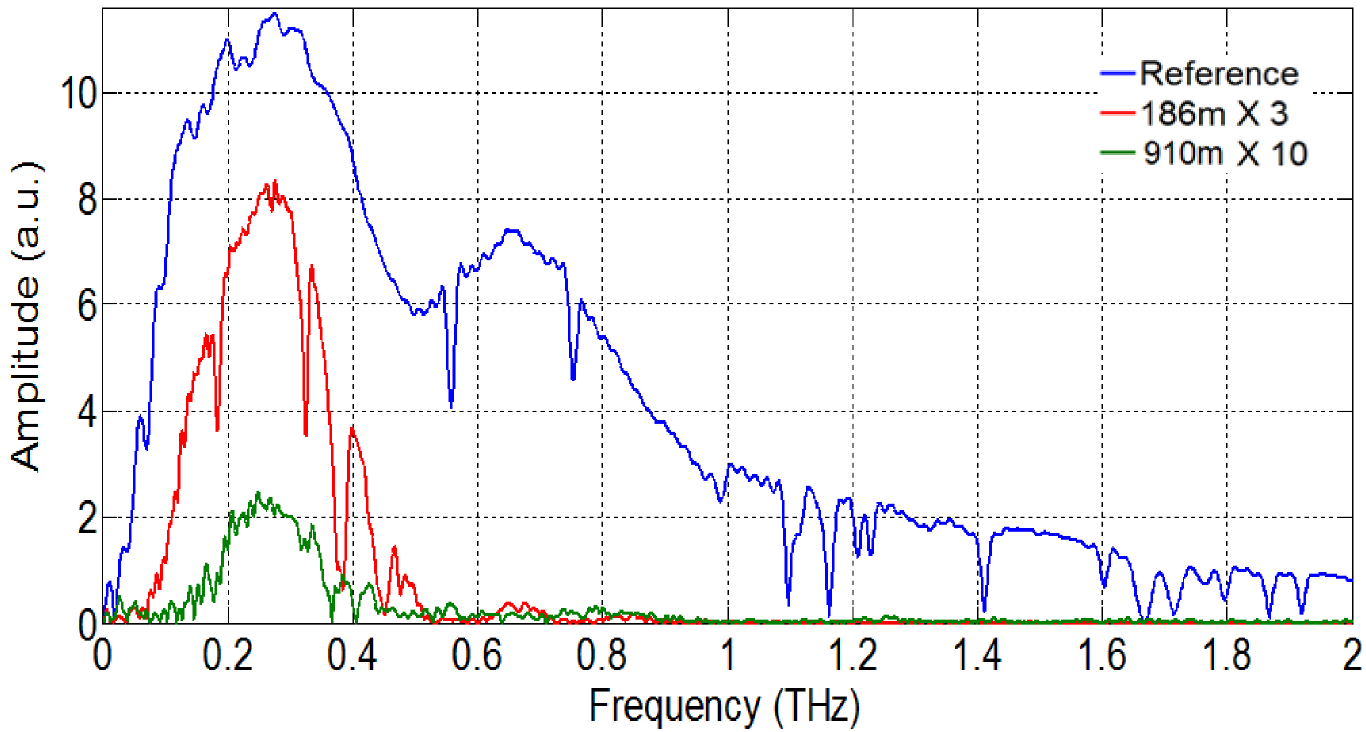
Photograph of 910m THz beam path



Measured THz pulses for different distance



Amplitude spectra for measured THz pulses

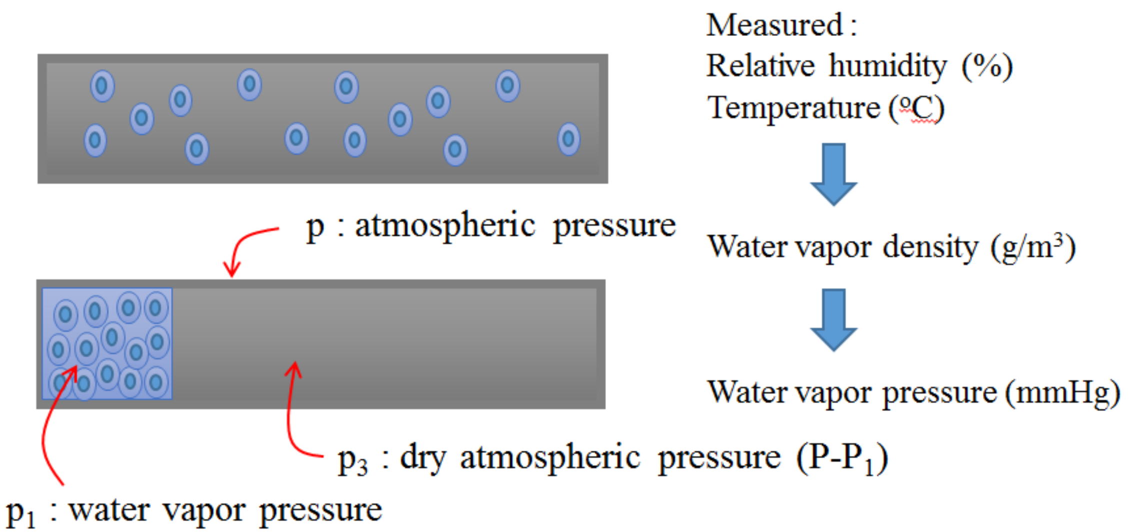


Total refractivity of the atmosphere

Essen & Froome formula (1951)

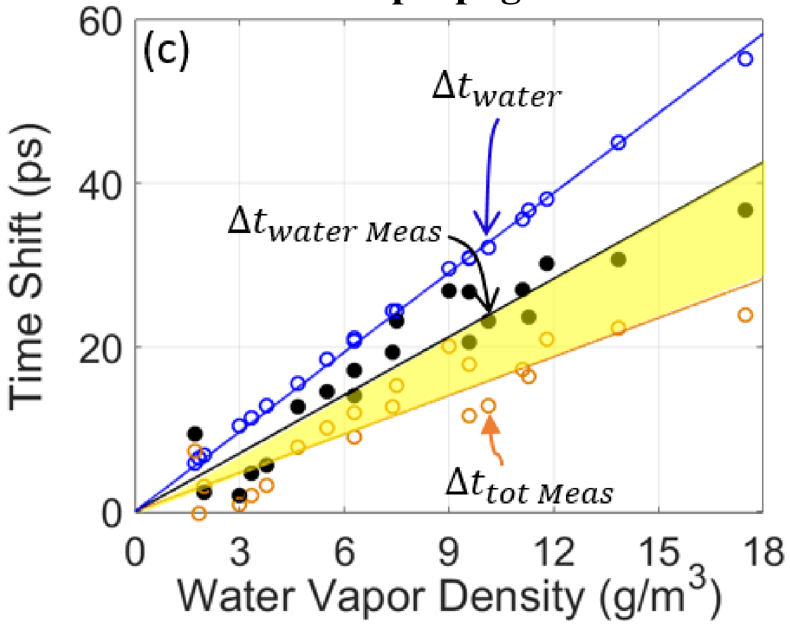
$$(n-1)10^6 = \frac{103.49}{T}p_1 + \frac{177.4}{T}p_2 + \frac{86.26}{T}\left(1+\frac{5748}{T}\right)p_3$$

p : atmospheric pressure = $p_1 + p_2 + p_3$ (mmHg=g/m^3),
Where p_1, p_2, and p_3 is dry atmospheric pressure, CO_2 pressure, and water vapor pressure, respectively. T is absolute temperature (K).

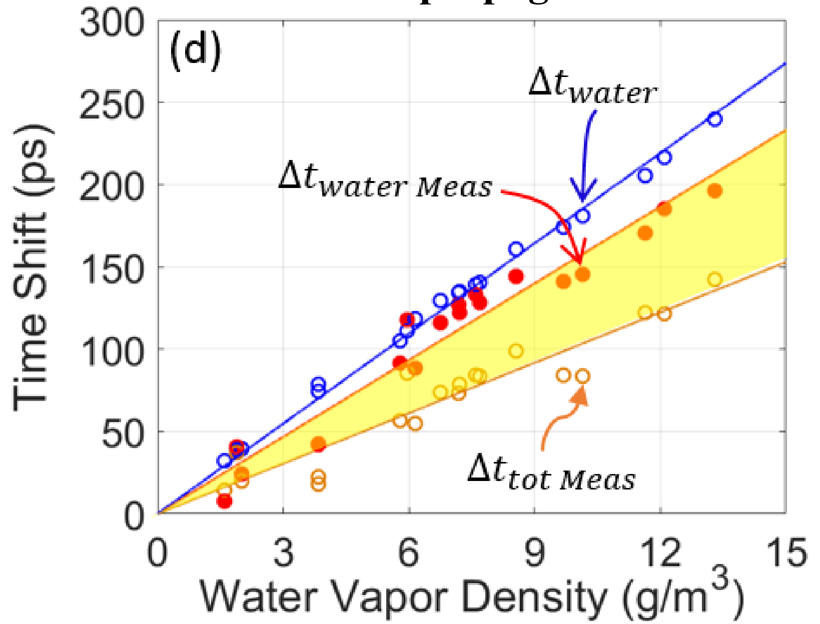


Time shift of theoretical calculations and experimental measurement

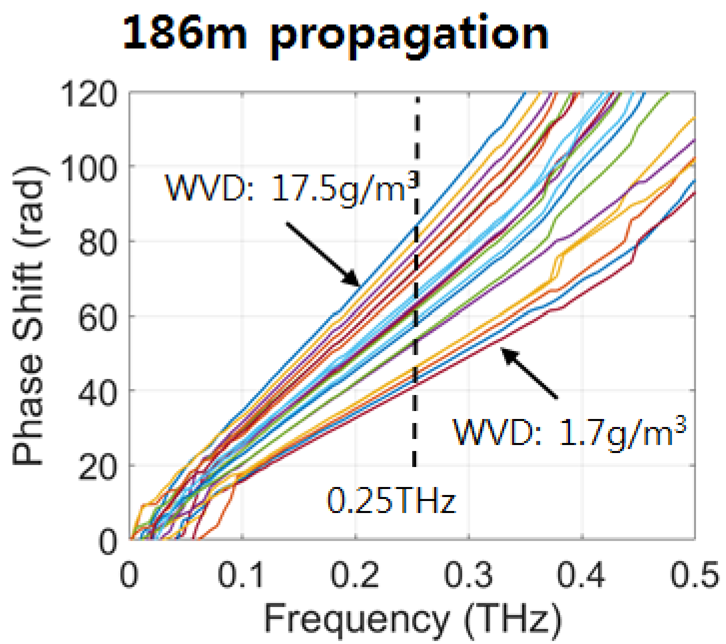
186m propagation

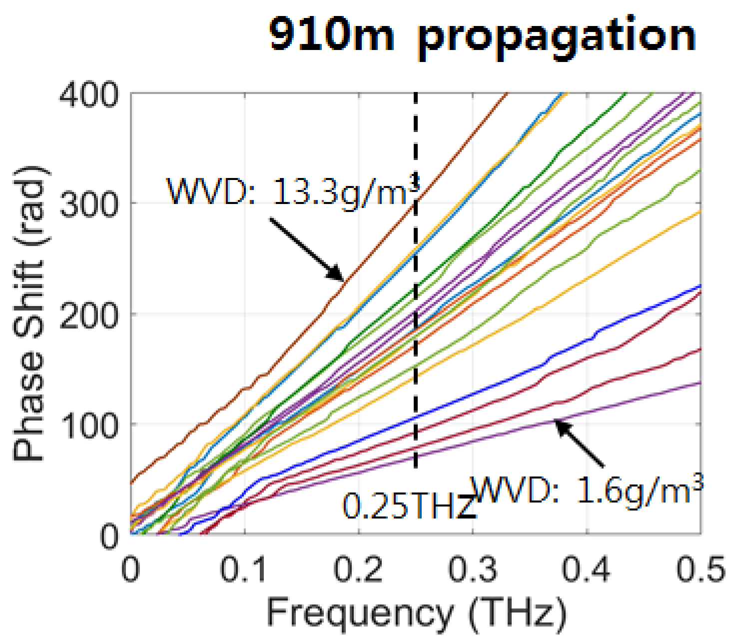


910m propagation



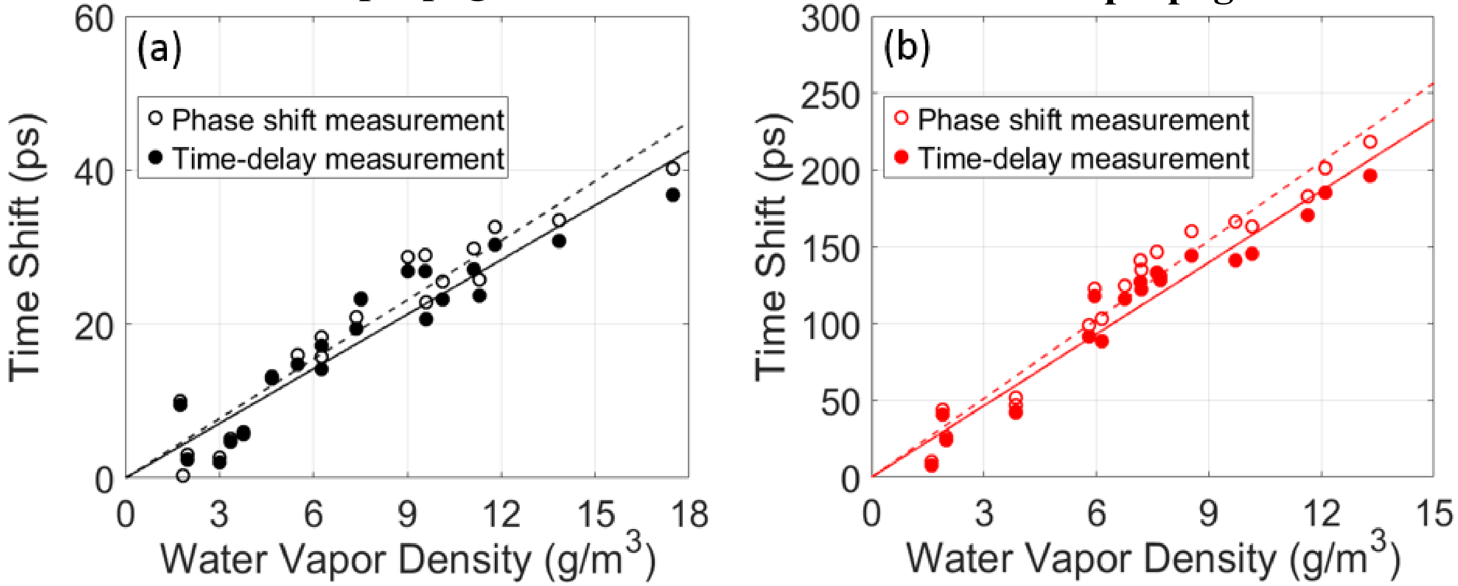
Time shift by phase shift measurement





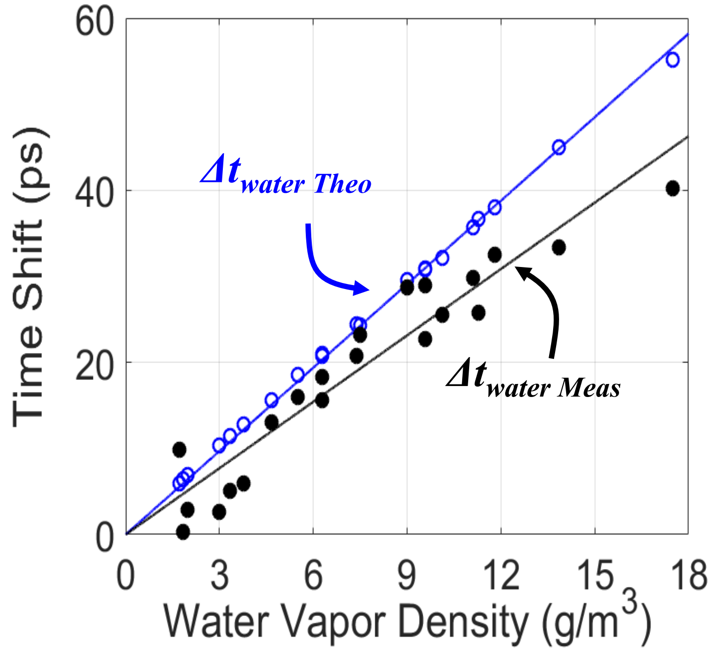
Comparison time shift by phase shift and time-delay measurements

186m propagation **910m propagation**

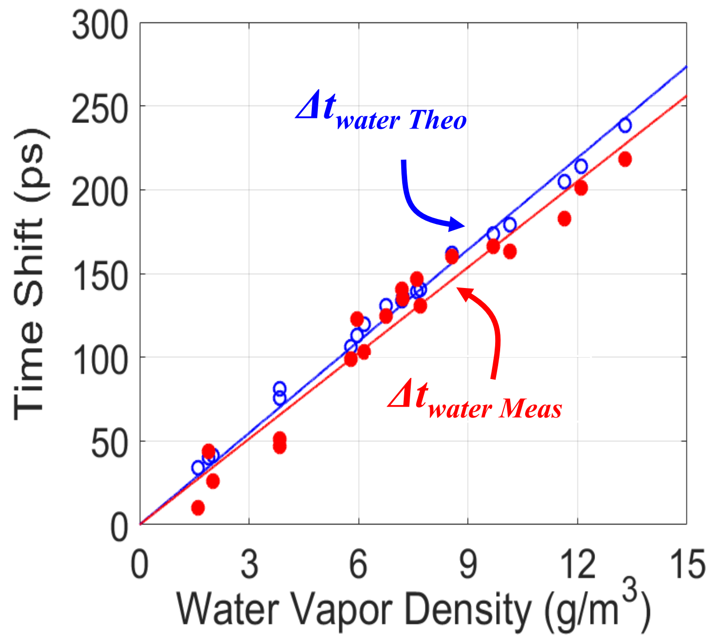


Comparison: theoretical calculations and experimental measurement

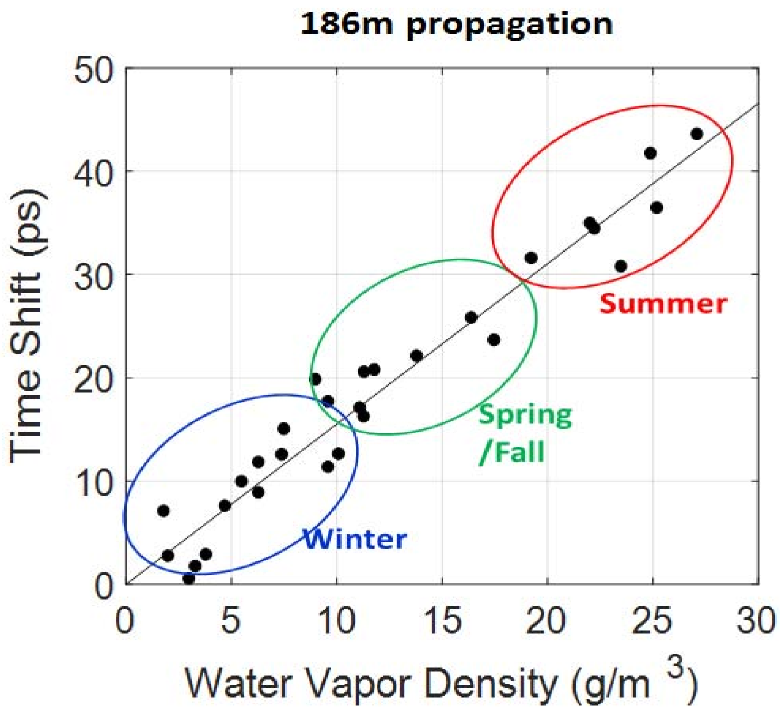
186m propagation

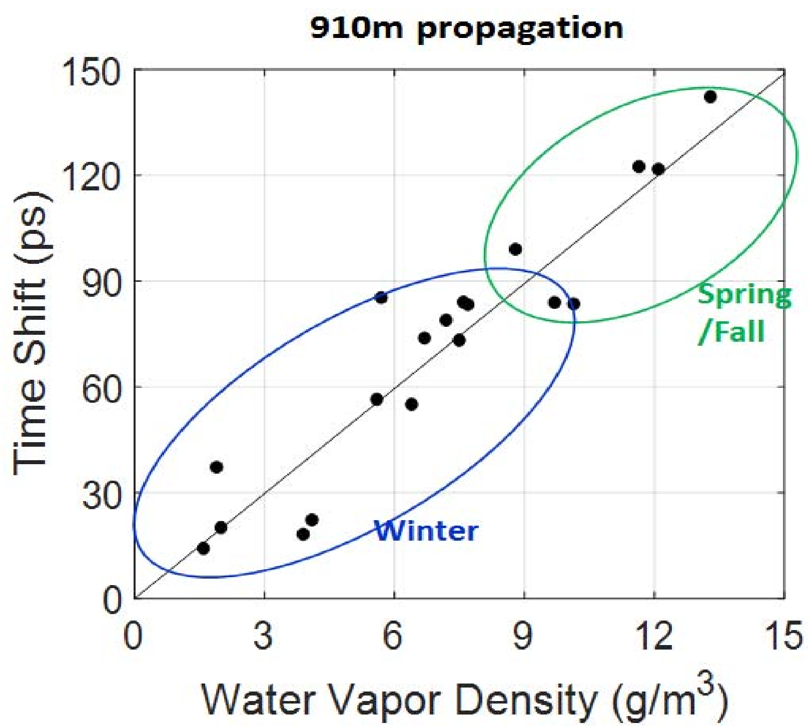


910m propagation

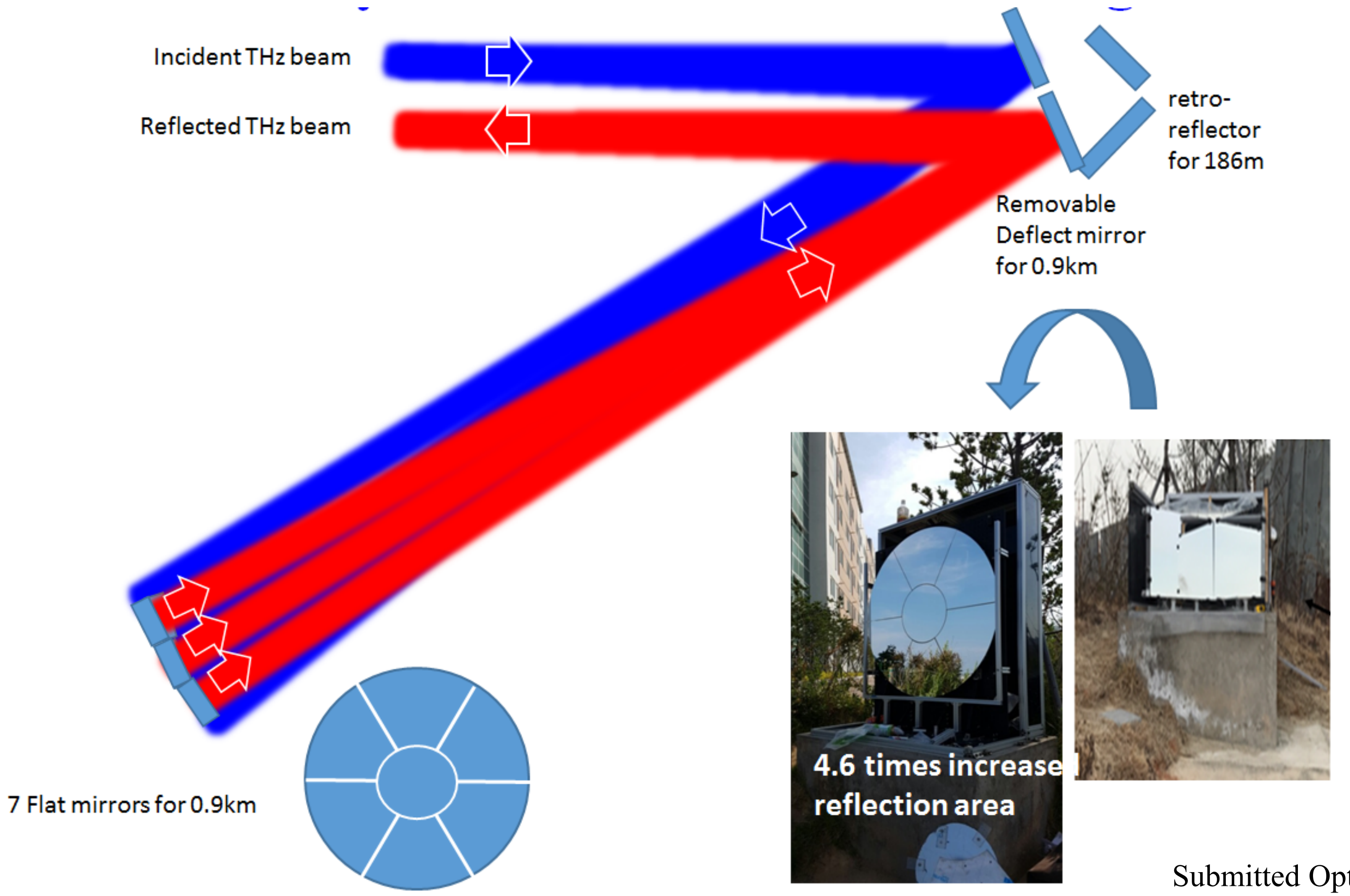


Seasonal (different WVD) measured time shift



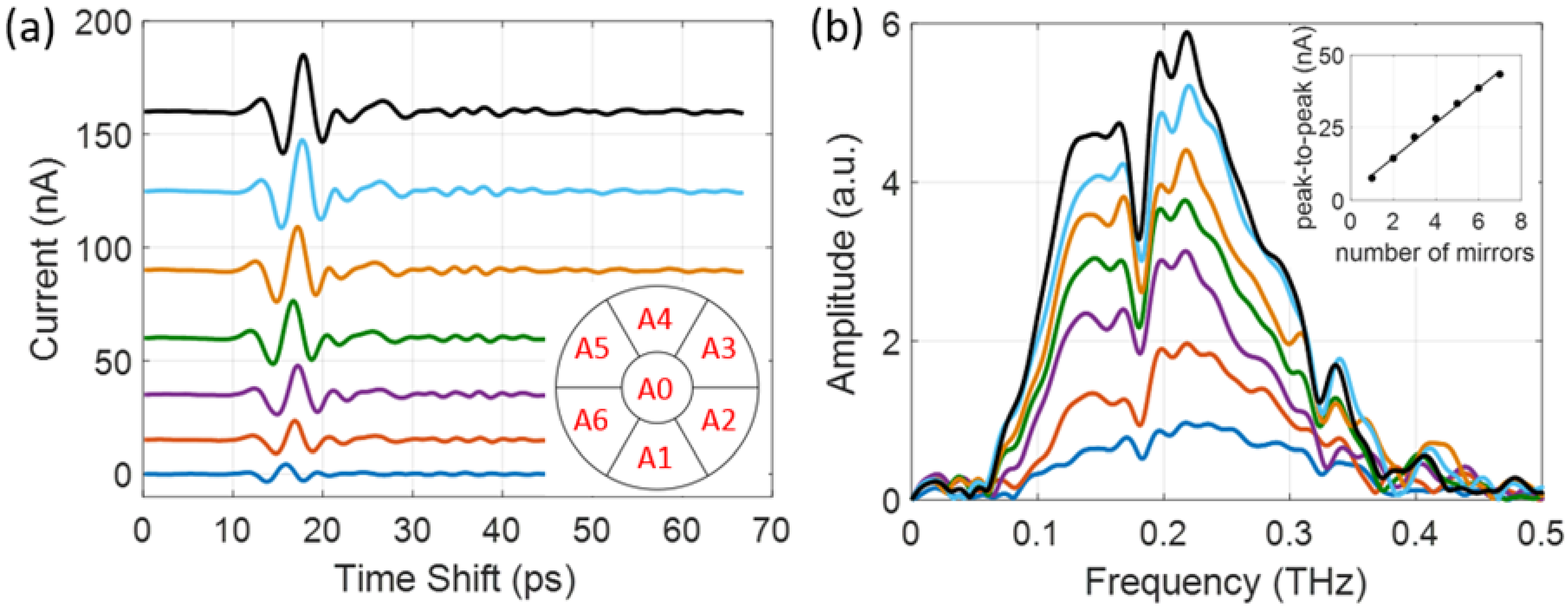


Mirror array to increase THz reflection signal

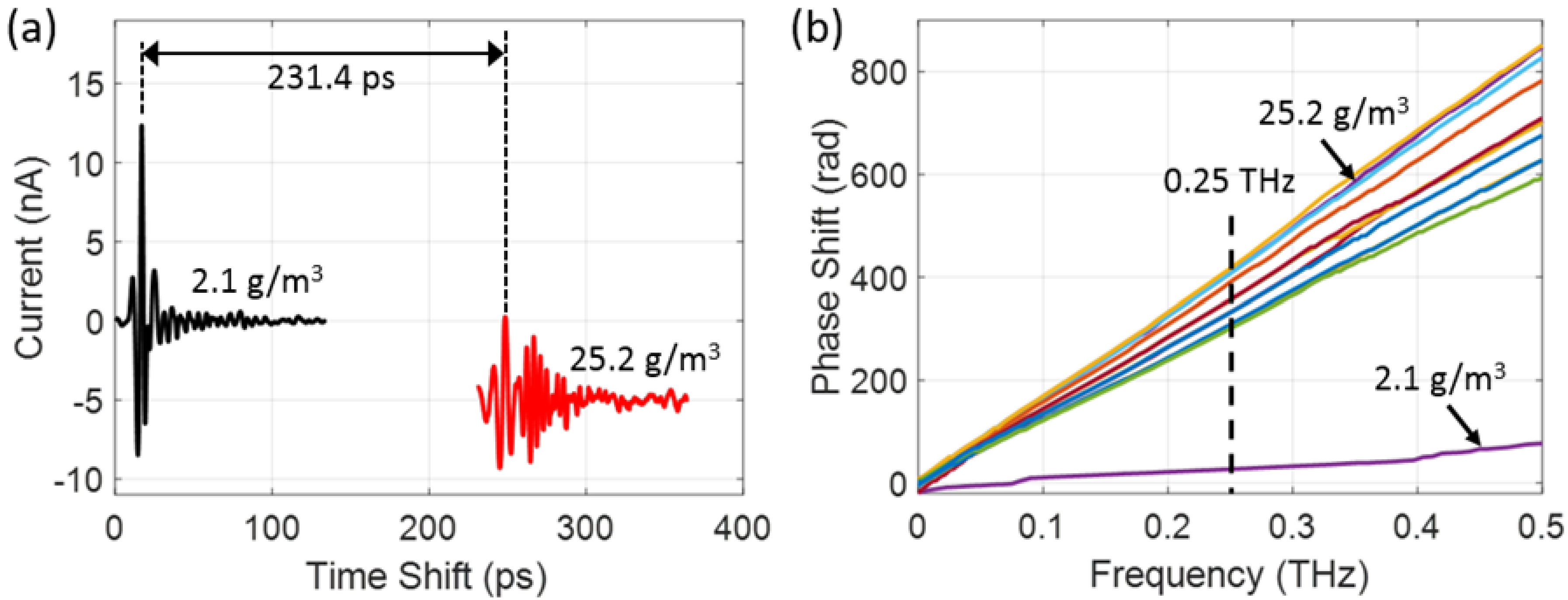


Submitted Optics Express [3]

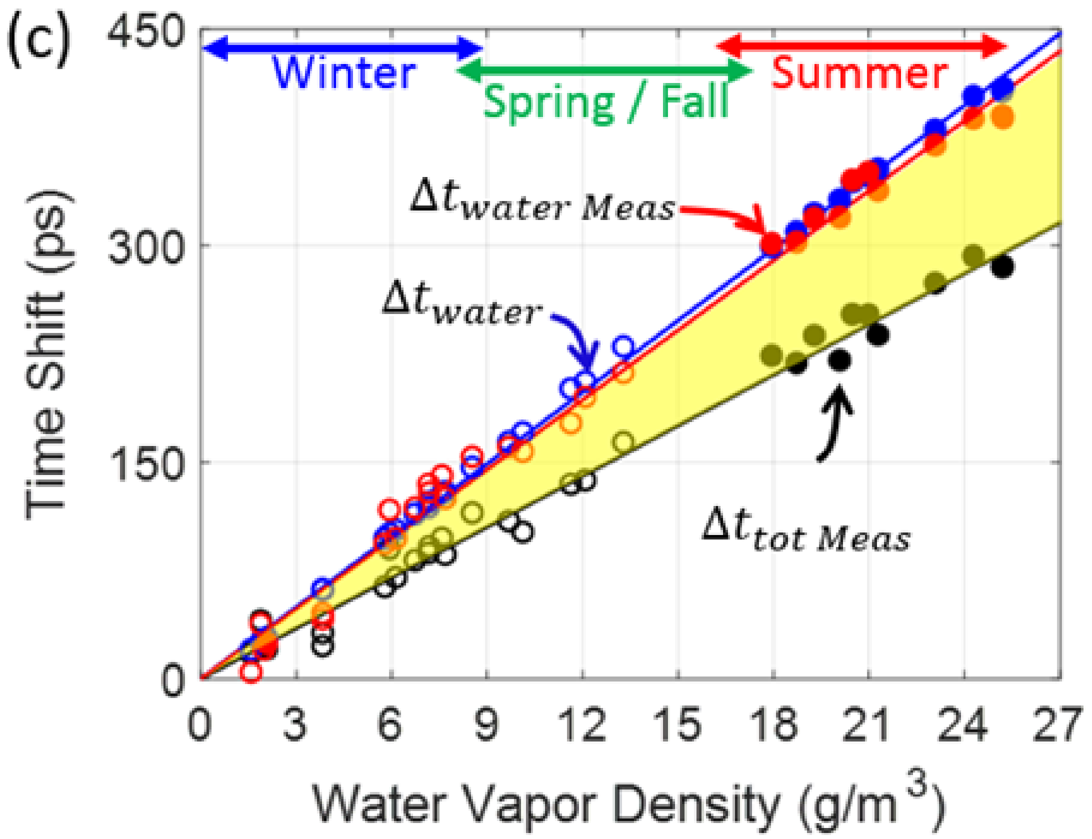
THz pulses reflected in each mirror combination of the seven-mirror array



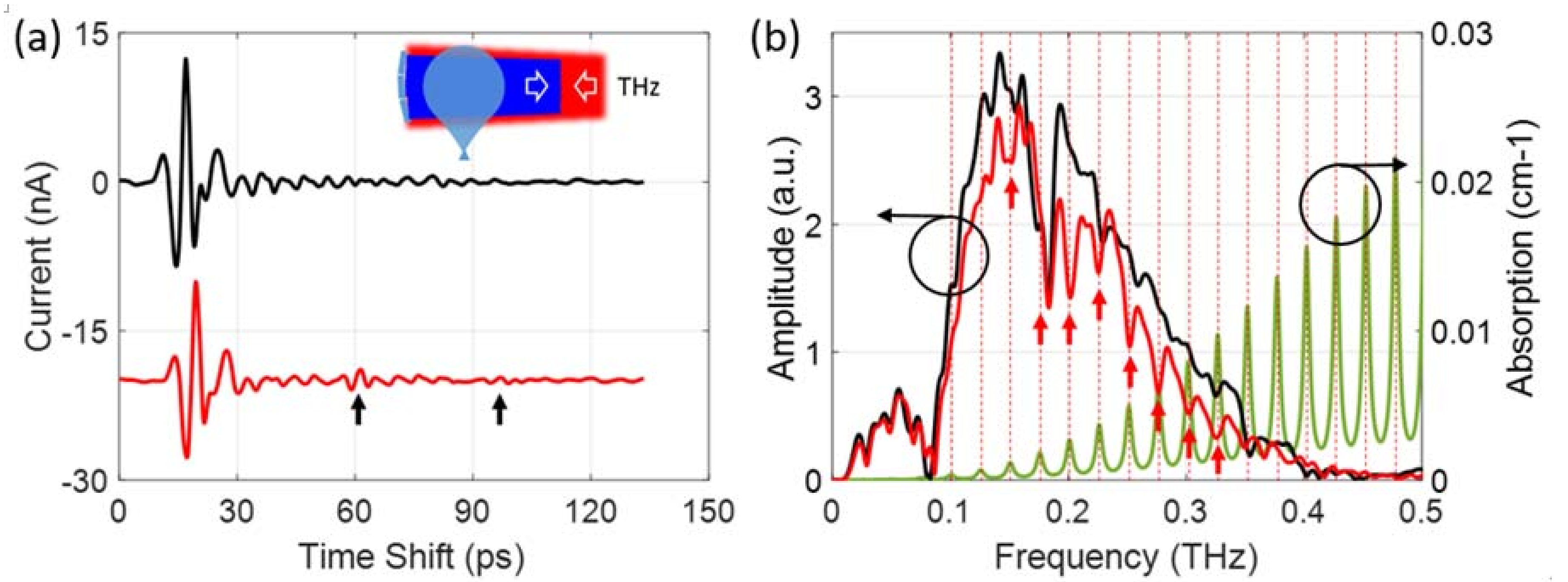
Measured time-delay and phase shifts



Comparison time shift caused by water vapor in the outdoor atmosphere



Measurement of N_2O gas located 455 m away from the Tx and Rx chips



Conclusions

186m measurement

•The THz pulses propagated through rain falling at 3.5 mm/h and snow falling at 2 cm/h equivalent to 2.0 mm/h rainfall.

•For calm weather, the transmitted THz pulse shapes and relative transit times were measured to a precision of 0.1 ps.

•To overcome the time shift for the sequentially measured THz pulses, introduced the fast scan method.

910m measurement

•The longest THz pulse propagation (910m) in the world.

•Measured water vapor density dependent (seasonal) time shift of THz pulse.

•Measured time shift and compared theoretical calculations.

•Measured N_2O gas resonances at 455 m away.

•Enable a new class of THz long-distance wireless communication, sensors, and spectroscopy.

References

- [1] E.-B. Moon, T.-I. Jeon, and D. Grischkowsky, “Long-path THz-TDS atmospheric measurements between buildings,” IEEE Trans. Terahertz Sci. Technol. 5(5), 742-750 (2015).
- [2] G.-R. Kim, T.-I. Jeon, and D. Grischkowsky, “910-m propagation of THz ps pulses through the atmosphere,” Opt. Express 25(21), 25422-25434 (2017).
- [3] G.-R. Kim, K. Moon, K. H. Park, J. F. O’Hara, D. Grischkowsky, and T.-I. Jeon “Remote N_2O gas sensing by enhanced 910-m propagation of THz pulses,” submitted Opt. Express (2019).