Alternate Nuclear Detection Mechanism Using Electromagnetic Waves

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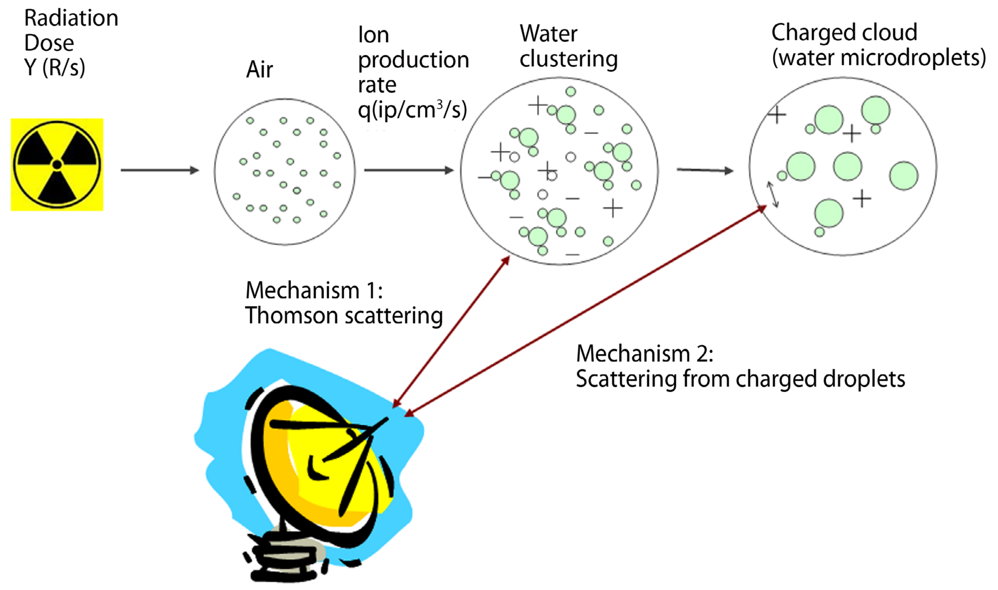
Argonne's new microwave detection mechanism has the potential for detecting nuclear radiation at distances greater than 1 kilometer.

Background

Microwave radar is known to detect highly dense charged columns of air from lightning, meteors, etc., due to a higher plasma frequency than the incident radar frequency. However, limited or no knowledge existed on radar detection of weakly ionized air at terrestrial conditions, especially for the scenario of radioactive ionization.

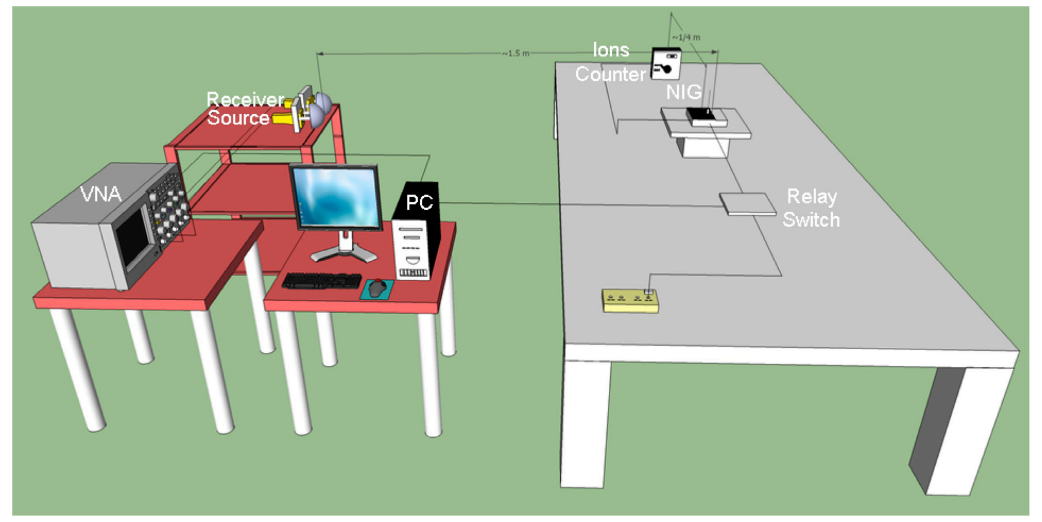
Using modeling and experiments, Argonne researchers have developed an alternate nuclear signature mechanism for remote detection of nuclear materials/radioactive plumes. The mechanism is based on electromagnetic scattering from radioactively induced ionization clouds in the air.



Sequence of ionization steps in air. Favorable microwave interaction is possible in the first step where coherent Thomson scattering from electrons occurs or from the enhanced scattering from charged water microdroplets as they form in time.

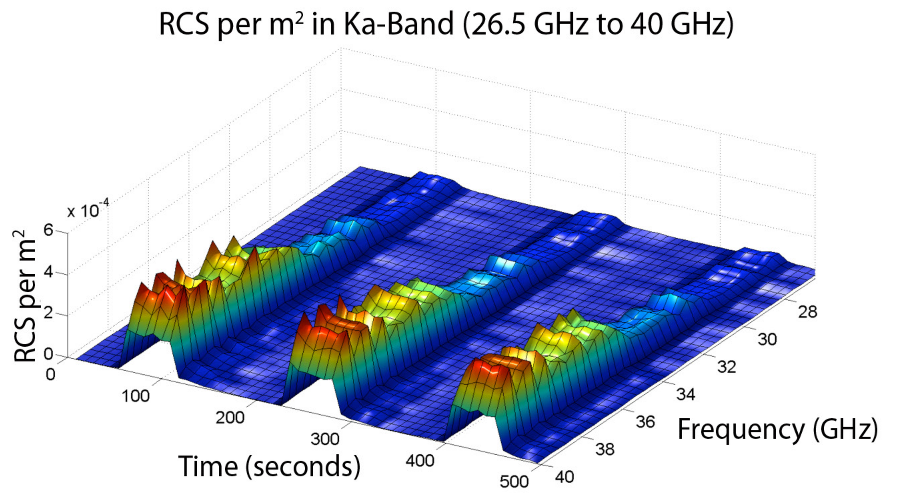
Microwave Measurement of Ionized Room Air

A negative ion generator (NIG) was used to generate approximately 10 million ions per cubic centimeters in air. The NIG mimics the ionization of air from a radioactive source. An Agilent vector network analyzer was used to sweep frequency and record the network scattering parameter S_{21} from 26.5 GHz to 40GHz (Ka-band). The source and detector were configured in a bistatic mode to measure the radar cross section (RCS) for different angles.

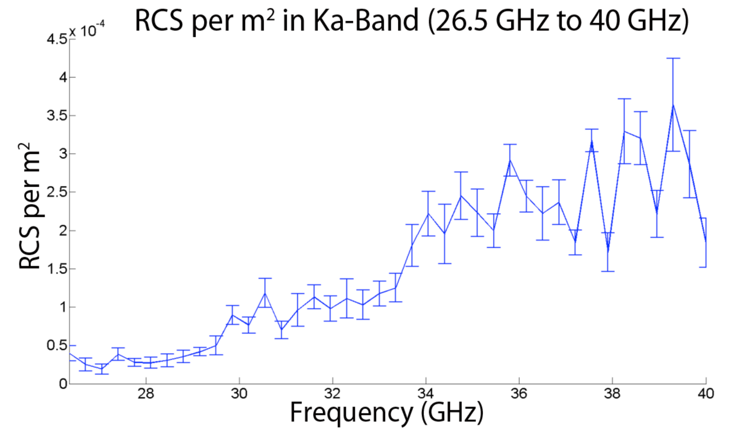


Experimental setup for microwave reflection measurement of ionized air.

- When the ionized air is present, the RCS increases on the order of 10^{-5} to 10^{-4} (m^2) over the whole band. This level of RCS per m^2 can be easily detected by current radar systems.



Measured RCS per m2 in the Ka-band (26.5 GHz to 40 GHz) for three NIG on-and-off cycles.

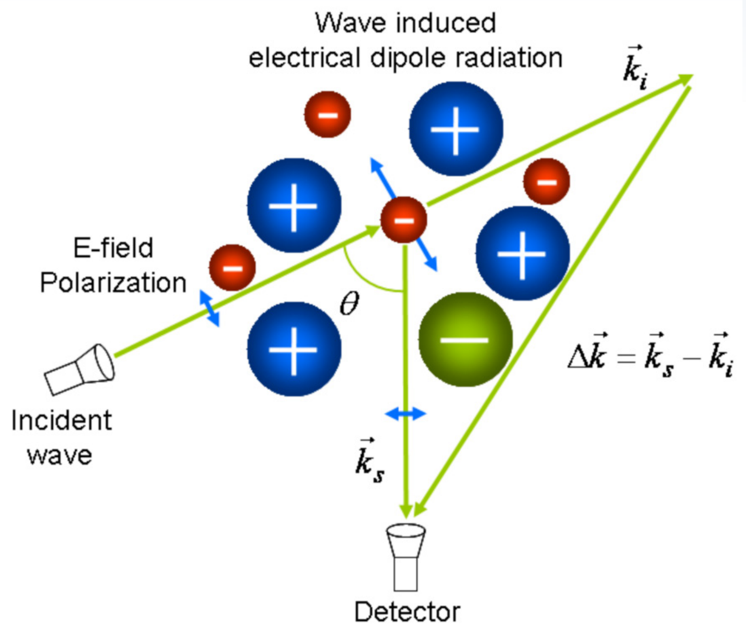


Averaged RCS per m² in the Ka-band (26.5 GHz to 40 GHz): the error bars show the standard deviation of the RCS per m².

- If the change of RCS per m^2 is averaged between when the NIG is on from when the NIG is off during the three NIG on-and-off cycles, the average RCS in the whole Ka-band can been seen in the figure at left. The resonant peaks are due to the inaccuracy of the system's calibration.

Coherent Thomson Scattering

The theory of phase coherent Thomson scattering may explain the measured RCS of ionized air at microwave frequencies. Thomson scattering is the elastic scattering of an electromagnetic wave by a free electron. The electric field of the incident wave accelerates the particle, causing it to emit an electromagnetic wave.



Thomson scattering process of electrons.

Phase-coherent Thomson Scattering

Electron density distribution for our Cs-137 source can be described by

$$n_e(\vec{r}) = n_0 \exp(-x^2/a^2)\exp(-y^2/a^2)\exp(-z/b)$$

Where a is source aperture, b is gamma mean free path in air ($b \approx 100m$) and $n_0 = n_e(0,0,0)$

Suppose plane wave is incident in –z direction

Backscattering cross-section can be calculated in cylindrical coordinates as

$$\sigma_b = \sigma_T n_0^2 \left| \int_0^\infty \int_0^\infty \int_0^{2\pi} e^{-r^2/a^2} e^{-z/b} e^{-i2kz} r dr d\theta dz \right|^2$$

Where $\sigma_T = 6.65 \times 10^{-29} m^2$ is Thomson scattering cross-section of single electron

Evaluating the integral, we obtain closed-form expression

$$\sigma_b = \sigma_T \pi^2 n_0^2 a^4 b^2 / (4b^2k^2 + 1)$$

For $\lambda << b$ this simplifies to

$$\sigma_b \approx \sigma_T n_0^2 a^4 \lambda^2 / 16$$

For $n_0 = 10^{13} m^{-3}$, $a = 1cm$, $\lambda = 1cm$. we have $\sigma_b = 4.2 \times 10^{-6} m^2$

Conclusion

This significant result points to remote sensing of nuclear sources from their ionization of air. The detection of charges from nuclear materials or radioactive plumes allows for remote sensing of nuclear proliferations events.

Future Efforts

- Further work is planned with radioactive sources and in the determination of optimal frequency band, minimum detectable charge density, and the role of humidity in the air.
- Additionally, the detection of RCS of ionized air may be able to shed light on formation of clouds and rain, and assist in the early monitoring of thunderstorms.

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