PROVIDENCE PHOTONICS

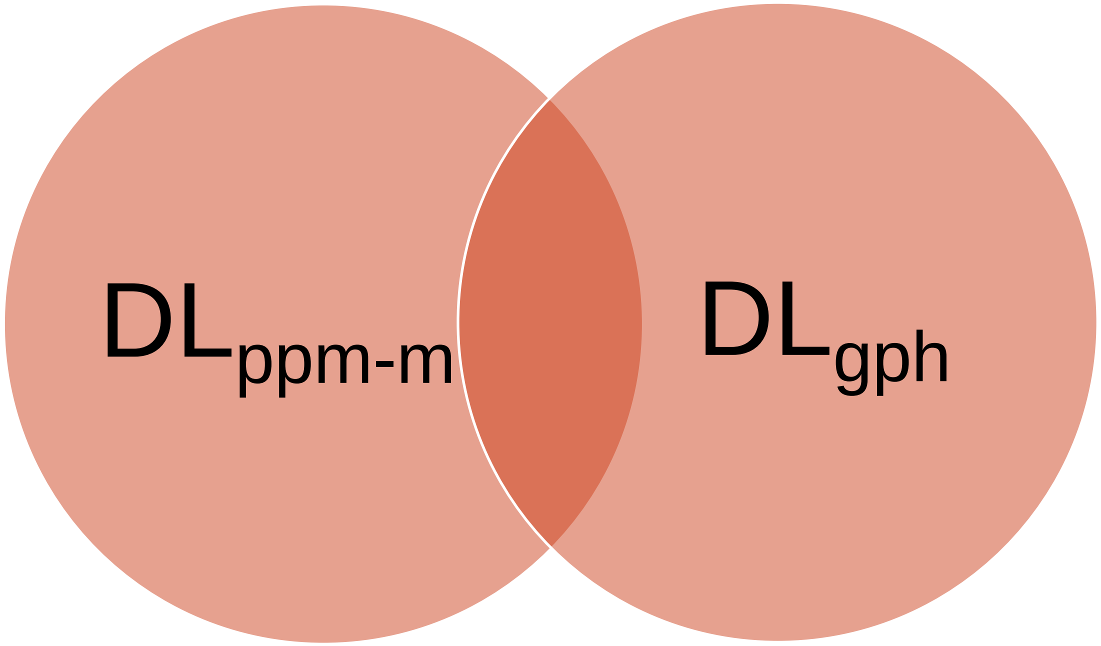
Detection Limits of Optical Gas Imaging

Presented by
Yousheng Zeng and Jon Morris
Providence Photonics

At
EPA Optical Gas Imaging Stakeholder Workshop
November 9-10, 2020

Two Approaches to OGI Detection Limits (DL)

- DL measured as gas concentration integrated along the optical axis, commonly expressed as ppm-m ($DL_{ppm\text{-}m}$)
  - It characterizes OGI camera’s ability to detect gas plumes at pixel level
- DL measured as mass leak rate (or volumetric leak rate), e.g., detection limit in leak rate of grams per hour (DL_{gph})



Factors Affecting OGI DL

- ΔT (=Apparent T of background – T of gas)
- Camera design
  - Sensor type (cooled vs. uncooled, sensor pitch, lens, etc.)
  - Bandpass filter
- Type of gas (IR spectrum, absorption coefficient)
- Distance
- Complexity/uniformity of background
- Dispersion conditions (wind, atmospheric stability, etc.)
- Additional factors with less impact to DL:
  - Plume polarity (absorptive vs. emissive)
  - Ambient T

$DL_{ppm\text{-}m}$ for a Given OGI Camera

- For a given OGI camera, gas, and ΔT, $DL_{ppm\text{-}m}$ at the pixel level can be expressed as Eq. (1)

$$\boldsymbol{DL_{ppm-m}} = \alpha\, [|\Delta \boldsymbol{T}|]^{\boldsymbol{\beta}} \qquad \textbf{Eq. (1)}$$

Where

ΔT = Background apparent temperature (T_B) – gas temperature (T_G)

If ΔT > 0, it's an absorptive plume (dark plume)

If ΔT < 0, it's an emissive plume (white plume)

α and β: constant for a given OGI camera and gas.

See Ref. for vales of α and β

Since $DL_{ppm\text{-}m}$ is based on a single pixel, distance is not explicitly expressed in Eq. (1). However, distance can impact $DL_{ppm\text{-}m}$ when the gas plume is smaller than the interpixel distance (i.e. when the plume is too small to "fill the pixel" at that distance)

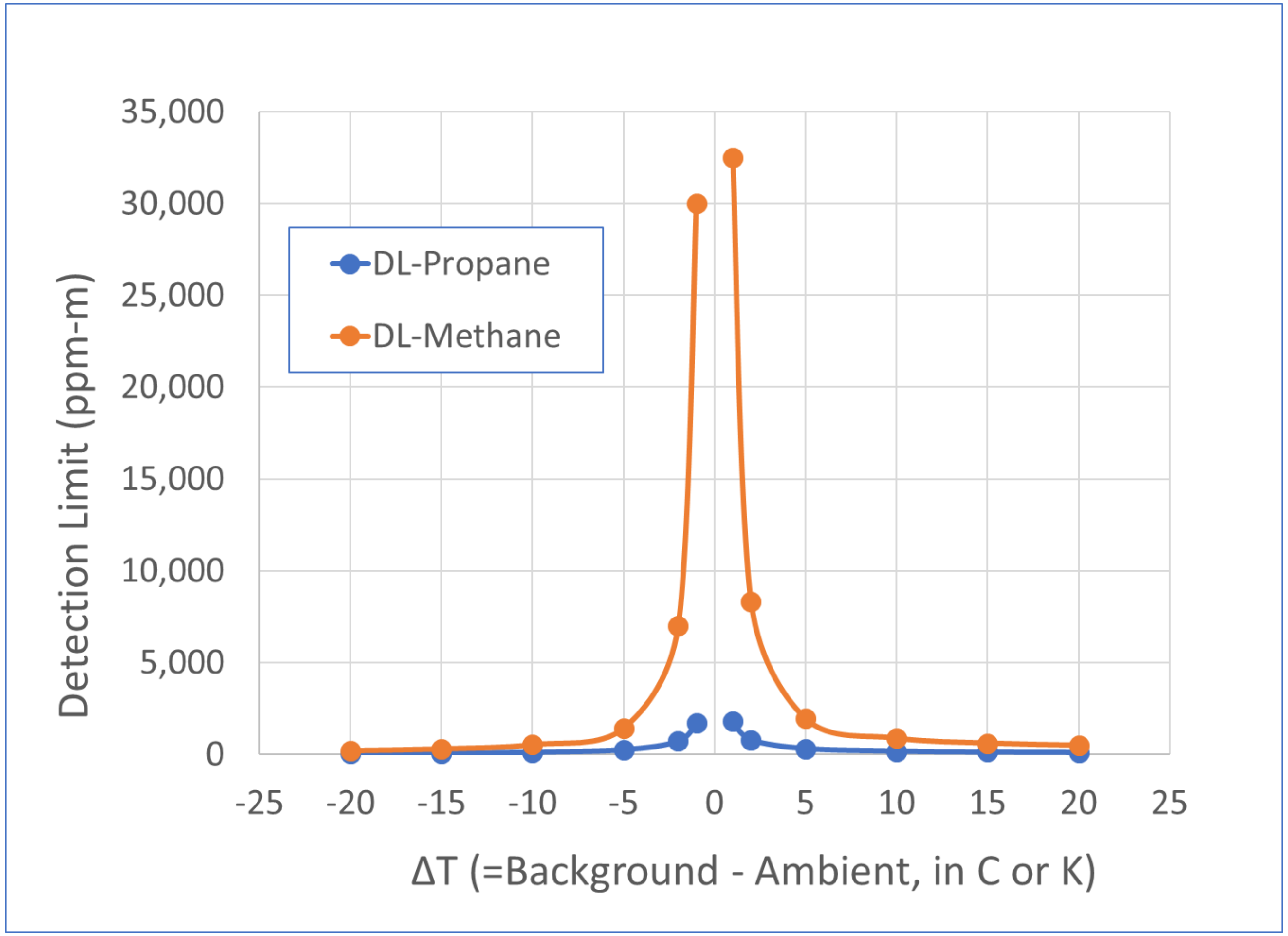
Ref. Y. Zeng and J. Morris; "Detection Limits of Optical Gas Imagers as a Function of Temperature Differential and Distance. *J. of Air & Waste Mgmt. Assoc.*, Vol. 69, No. 3, pp. 351-361

https://www.tandfonline.com/doi/full/10.1080/10962247.2018.1540366

$DL_{ppm\text{-}m}$ as a function of ΔT

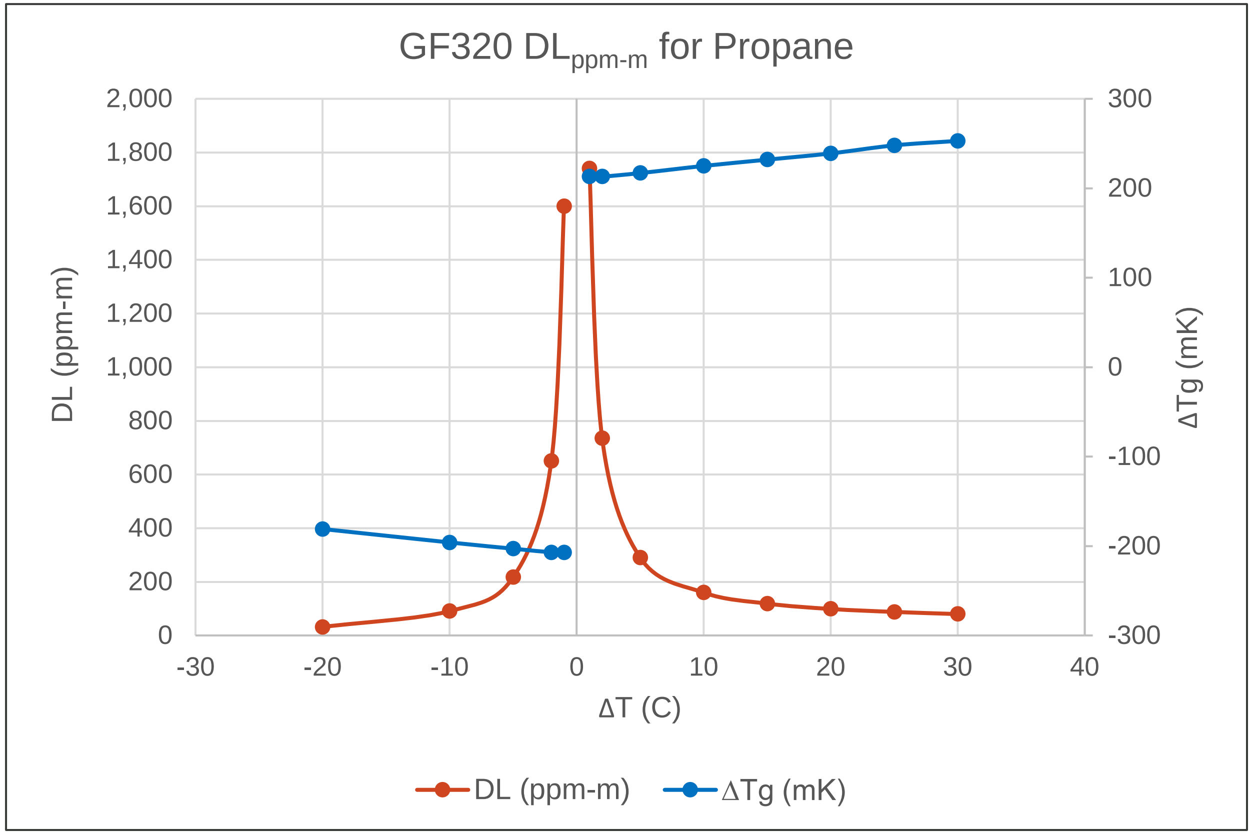
- OGI's ability to detect a gas leak rapidly deteriorates (high $DL_{ppm\text{-}m}$) as ΔT approaches zero from either positive or negative side of the chart. The $DL_{ppm\text{-}m}$ vs. ΔT curves become relatively flat when $|\Delta T| > \sim 5\ ^{O}C$.
- Propane is much easier to detect than methane (lower DL than methane).
- DL is slightly lower for emissive plume (negative ΔT) than absorptive plume.

FLIR GF320 Detection Limit as a function of ΔT



ΔT_g – Temp change due to presence of gas plume

- The constants α and β in Eq. (1) will vary depending on what threshold is used for plume recognition. We have used 1% contrast as the threshold, i.e., gas plume pixels must have at least 1% contrast against background pixels to be discernable by an observer (~2-3 shades of a typical 256-gray scale B&W display).
- The 1% contrast in the image corresponds to certain temp difference, i.e., the temp difference caused by the same amount of gas that caused 1% contrast.



- ΔT_g is relatively constant (~200 mK corresponding to the 1% contrast) while amount of gas is dramatically different
- When $|\Delta T|$ is lower, more gas (higher ppm-m) is required to generate the same ΔT_g or the same contrast

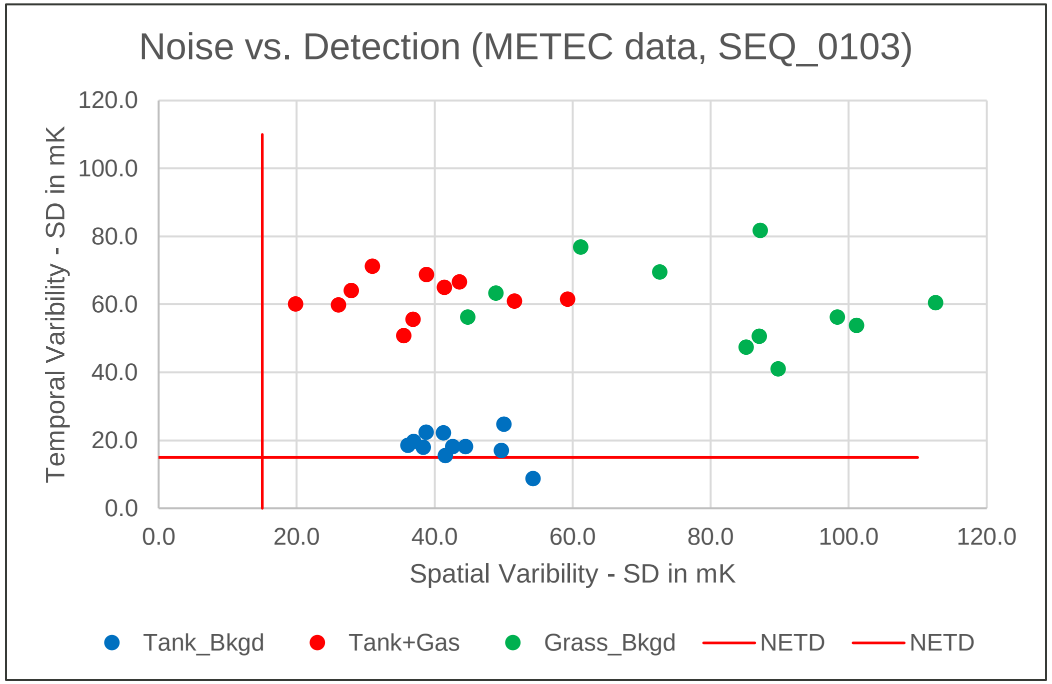
How Does the 1% Contrast Threshold Compare to the Camera NETD?

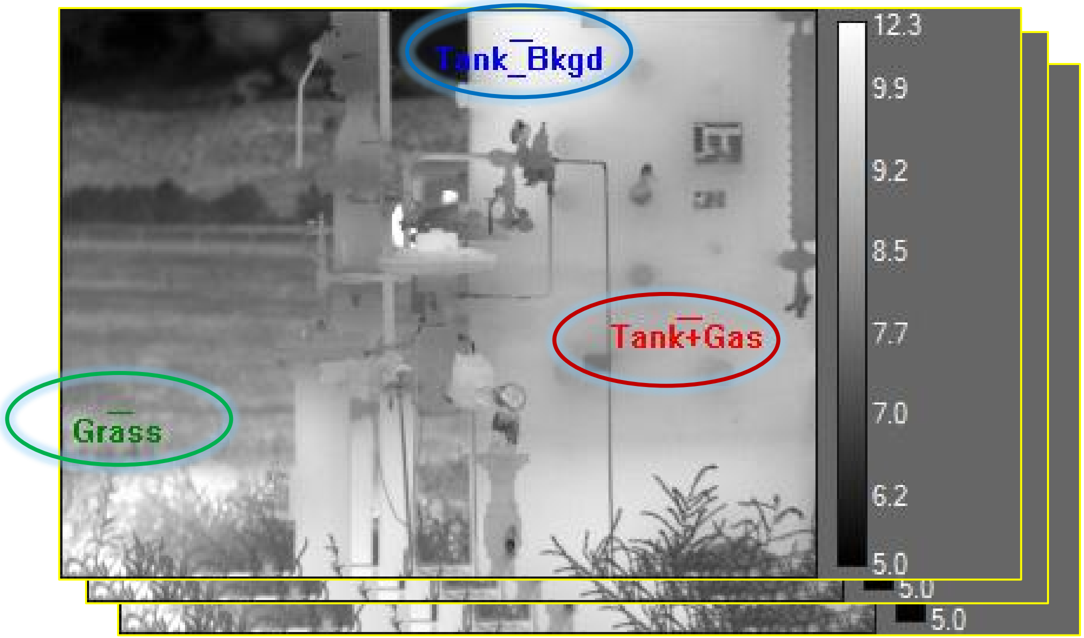
- Noise Equivalent Temperature Difference (NETD)
  - Standard performance specification for IR cameras
  - Measure of the frame-to-frame variability due to sensor noise
- Theoretically, if ΔT_g > NETD, gas plume should be detectable.
  - NETD for a FLIR GF320 is 15 mK
  - A 1% contrast corresponds to a ΔT_g around 200 mK for propane, an order of magnitude higher than the NETD.
- In practice, a ΔT_g higher than NETD is likely needed
  - How much higher?
  - We need to examine spatial variability we well

Camera Model	Camera Type	NETD (mK)
FLIR GF320/GFx320	Cooled, MWIR	15
FLIR GF620	Cooled, MWIR	20
FLIR GF77	uncooled, LWIR	50

Is the 1% Contrast Threshold Too High?

- An example take from a test at METEC
- Measured both temporal (11 sequential frames) and spatial variability (11 horizontal pixels in this case)
- Calculated Standard Deviation (SD) in 3 small areas in the image
- Small sample, but illustrative

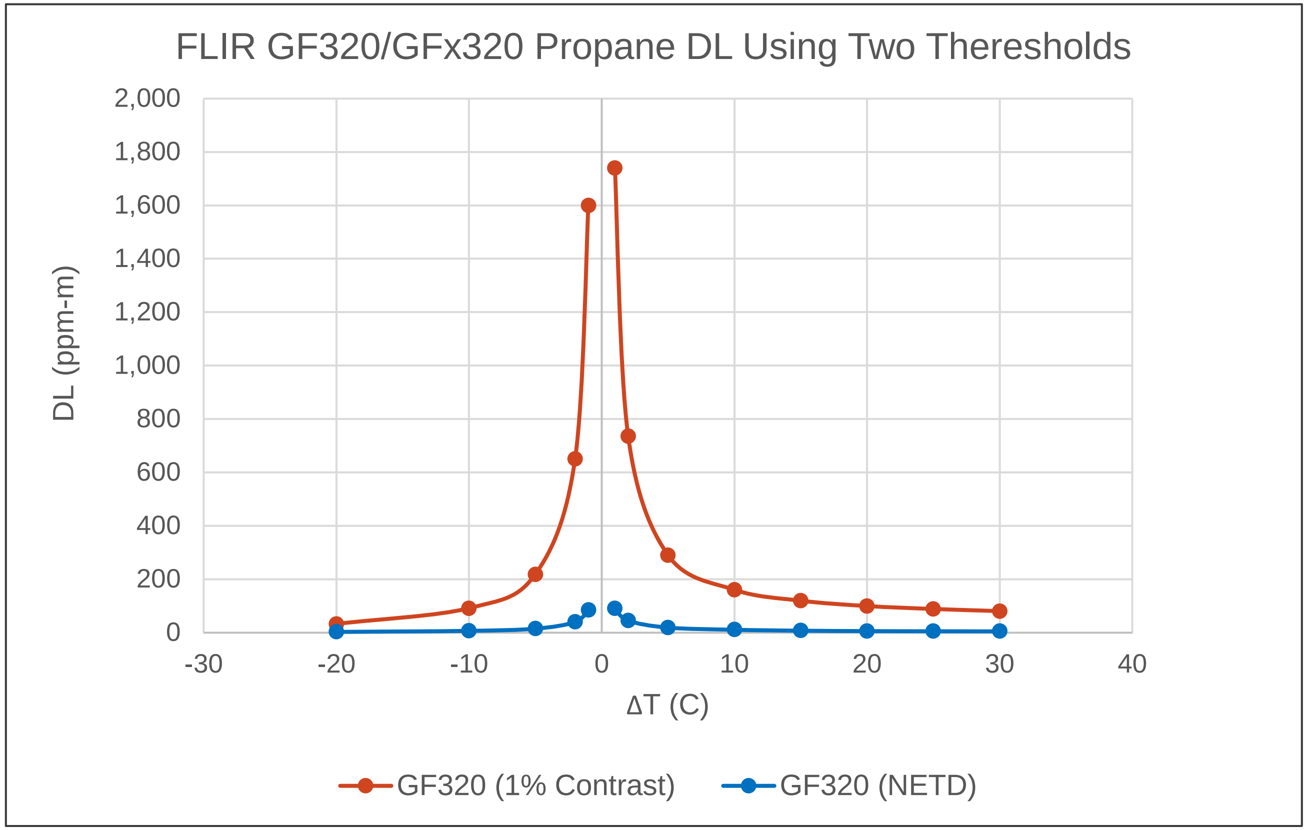




- For the complex background (grass), temporal and spatial variability is comparable or higher than the variability caused by gas plume. A 1% contrast (or ΔT_g ~ 200 mK) will provide ~ 2x or 3x SD for plume recognition and it seems very reasonable
- For a uniform background (tank), a contrast threshold lower than 1% will likely allow for plume recognition.

$DL_{ppm\text{-}m}$ Based on 1% Contrast vs. NETD

- NETD based DL is 1-2 orders of magnitude lower than 1% Contrast based DL. It may not be a realistic DL in many real-world cases. However, it is a useful benchmark for comparing OGI cameras.
- 1% Contrast based DL should be very robust even under challenging environmental conditions.
- $DL_{ppm\text{-}m}$ is proportional to NETD or contrast threshold if all other conditions, such as ΔT, are the same



GF320 propane DL based on different thresholds

(ΔT = 10 C)

Threshold for Recognition	DL (ppm-m)	Conc (ppm) if L=0.1m	Corresponding ΔTg (mK)
1% Contrast	160	1,600	225
0.5% Contrast	79	790	113
NETD	11	110	15

Camera Sensitivity and IR Spectrum Region

FLIR GF620

- FLIR GF620 has a higher pixel resolution than GF320 (640x480 vs. 320x240), but slightly lower NETD (smaller detector pitch, 15 µm vs. 30 µm). As a result, its $DL_{ppm\text{-}m}$ is slightly higher than GF320.

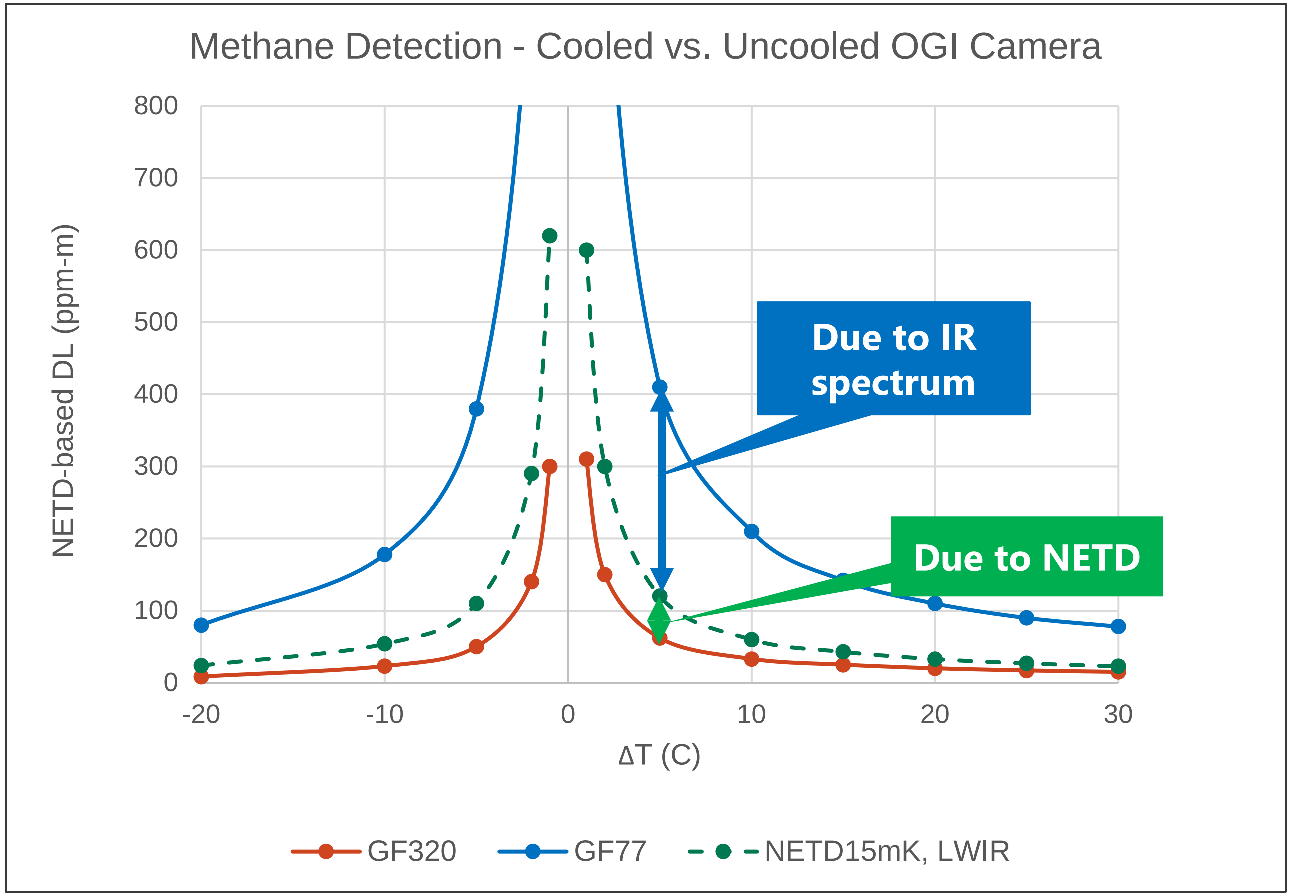
FLIR GF77

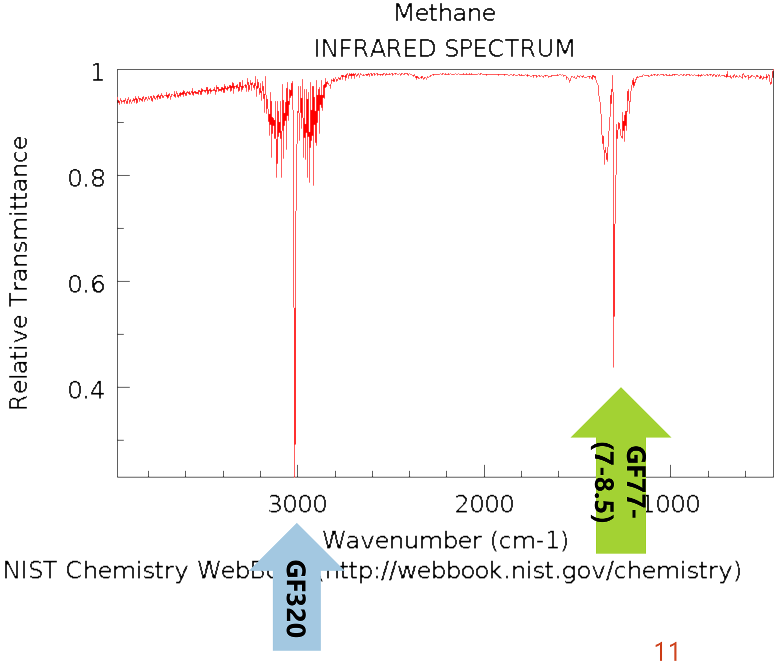
- FLIR uncooled camera GF77 is less sensitive and it works in LWIR. Its NETD and $DL_{ppm\text{-}m}$ are significantly higher.
- The effect on DL is due to both its NETD and IR spectrum region.

Camera Model	Camera Type	NETD (mK)	Propane DL @ ΔT=10C (ppm-m)
FLIR GF320/GFx320	Cooled, MWIR	15	11
FLIR GF620	Cooled, MWIR	20	14
FLIR GF77 (7-8.5)	Uncooled, LWIR	50	1,060

Methane Detection - Cooled vs. Uncooled Cameras

- We know an uncooled camera is less sensitive and has a higher DL, but why?

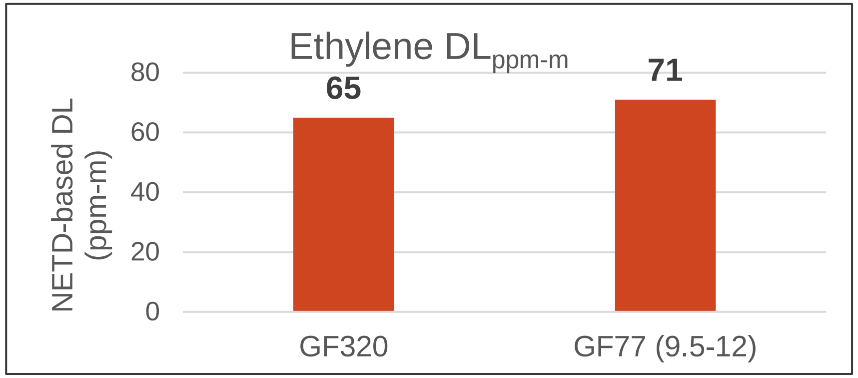




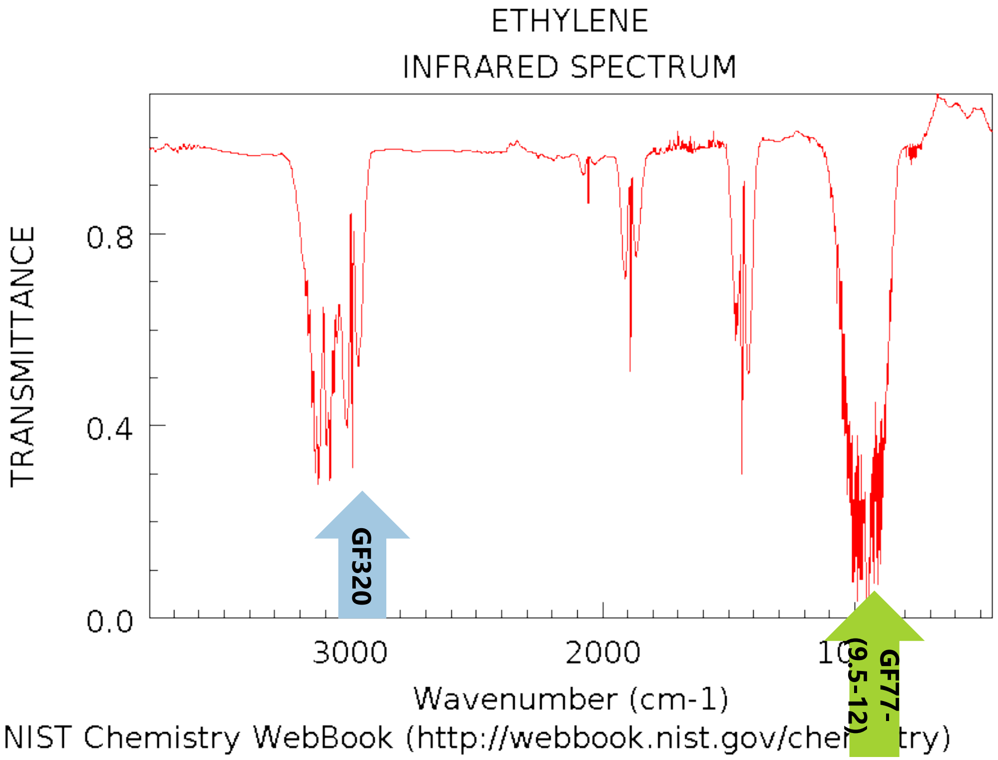
NIST Chemistry WebBook (http://webbook.nist.gov/chemistry)

Can Uncooled Camera Be Used in Downstream Applications?

- Methane is not a primary concern in downstream applications, but other gases may be.
- Use ethylene as a case study for downstream applications



- For ethylene, an uncooled camera can achieve comparable sensitivity as a cooled camera at significantly lower cost
- Over 240 gases are expected to have better DL than ethylene. Many of these gases are commonly found in downstream facilities.
- Field changeable filters make gas-specific leak detection (and potentially quantification)



NIST Chemistry WebBook (http://webbook.nist.gov/cher try)

NETD-based $DL_{ppm\text{-}m}$ vs. NECL

- Noise Equivalent Concentration Length (NECL) is proposed by FLIR (Sandsten et. al.).
- Both methods are measured as ppm-m.
- Both methods are based on ideal lab-controlled background conditions.
- NECL is a function of both ΔT and CL; and NECL at CL=0 ppm-m is recommended.
- NETD-based $DL_{ppm\text{-}m}$ is derived from NETD, and it is a function of ΔT only.
- Based on published NECL data, the NETD-based DL is higher than NECL, but it is close to the NECL if NECL is based on CL=1000 (see Methane in the table).

NETD-based $DL_{ppm\text{-}m}$ and NECL
(ΔT = 10 C)

Gas - Camera Model	DL (ppm-m)	NECL (ppm-m) @ CL=0 / [@ CL=1000]
Methane – GF320	33	13 [40]
Methane - GF77(7-8.5)	210	100
Propane – GF320	11	
Propane – GF77(7-8.5)	1060	400
Ethylene – GF320	65	
Ethylene – GF77(9.5-12)	71	20

Detection Limit in grams per hour (DL_{gph})

- For a given OGI camera and gas, DL_{gph} can be expressed as Eq. (2)

$$DL_{gph} = c \cdot DL_{ppm-m} \cdot d^2 \cdot w \cdot \frac{P}{T} \cdot \frac{MW}{R} \qquad \text{Eq. (2)}$$

Where

c = A constant specific to an OGI camera. The c values for FLIR GF300/320 and GFx320 cameras are listed in the table below

w = A variable that is influenced by dispersion conditions (primarily wind speed and gas exit velocity from the leak point). For typical dispersion conditions, a default value 35 m^3/l-hr is used.

d = Distance from the camera to the gas plume, in meters

P = Pressure of the gas in atm.

T = Temperature of the gas in Kelvin

MW= Molecular weight of the gas, g/gmol

R = Ideal gas law constant, 0.08206 atm-l/gmol-K

The value of constant c for three lenses of FLIR GF300/320 camera (based on 1% contrast detection threshold).

Lens	23 mm	38 mm	92 mm
c	6.17×10^{-5}	2.25×10^{-5}	3.86×10^{-6}

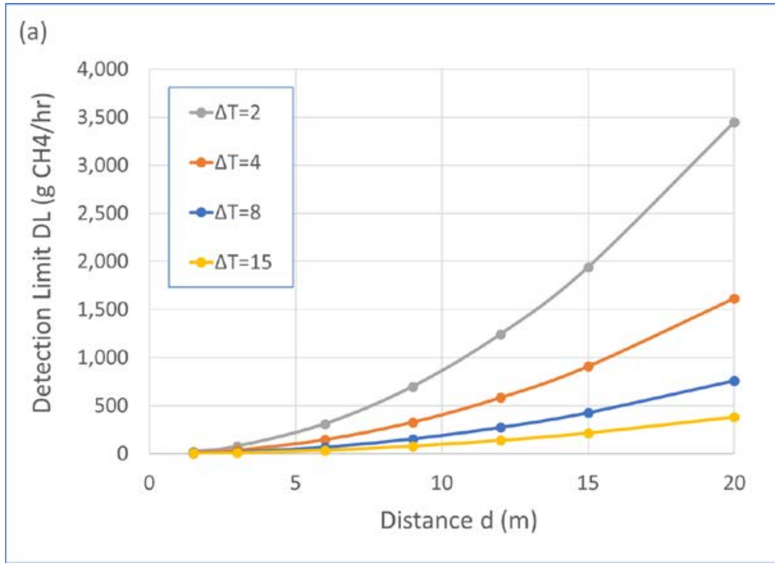
Detection Limit in grams per hour (DL_{gph})

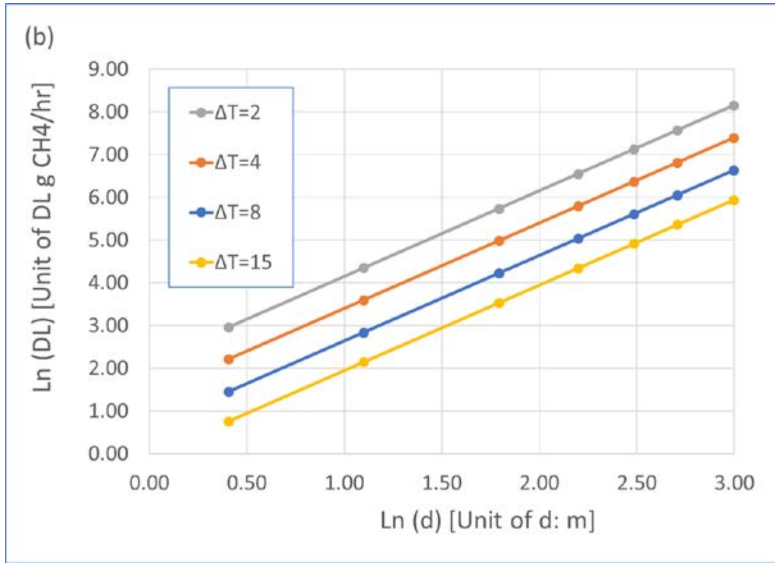
- Eq. (2) can be simplified to the following form:

$$\boldsymbol{DL_{gph}} = \mathbf{a} \cdot |\boldsymbol{\Delta T}|^{-\boldsymbol{b}} \cdot \boldsymbol{d}^{2} \qquad \textbf{Eq. (3)}$$

Where: a and b are constants for a given camera, lens, common wind conditions, and standard atmospheric conditions.

- OGI detection limit expressed as g/hr. (or lb/hr.) is a function of ΔT and distance, and both parameters are readily measurable!





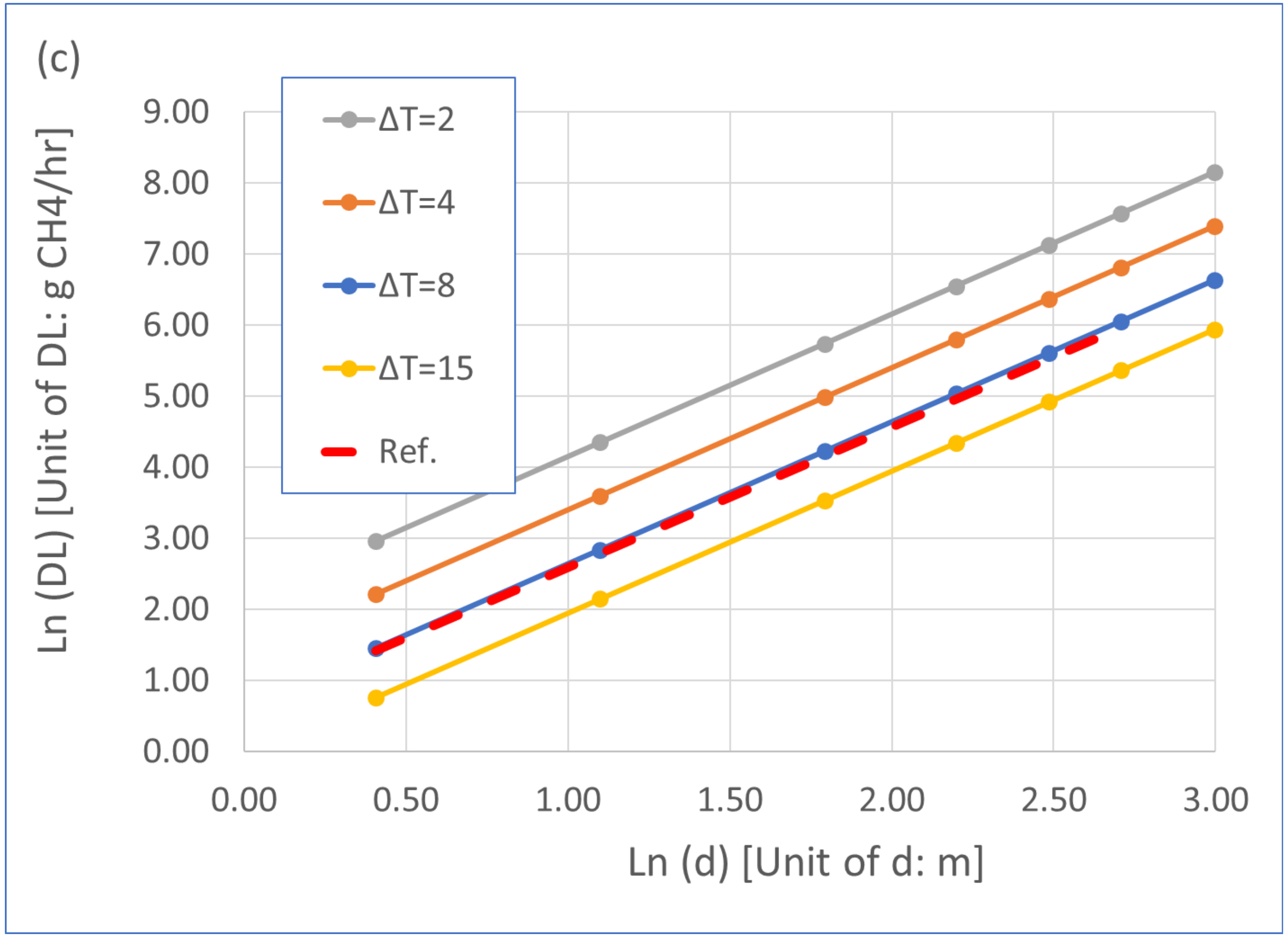
Data based on FLIR GF320

DL_{gph} for Methane

- Chart based on Eq. (3) in previous slide
- Chart (a) in normal scale and Chart (b) in log scale
- DL_{gph} is a cluster of curves for different ΔT.
- At each ΔT, DL_{gph} is proportional to d^2.

Derived DL_{gph} for Methane compared to other research

- Ravikumar, et. al. (2018), used an empirical method to determine detection limit and accounted for distance, but did not include ΔT.
- The detection limit equation empirically derived by Ravikumar, et. al. matches perfectly with Eq. (3) for ΔT = 8 ^{O}C.
- Significance:
  - Analytically derived Eq. (3) matches empirical work independently done by other researchers – a validation of the method
  - Without factoring ΔT, OGI detection capability can be off by an order of magnitude

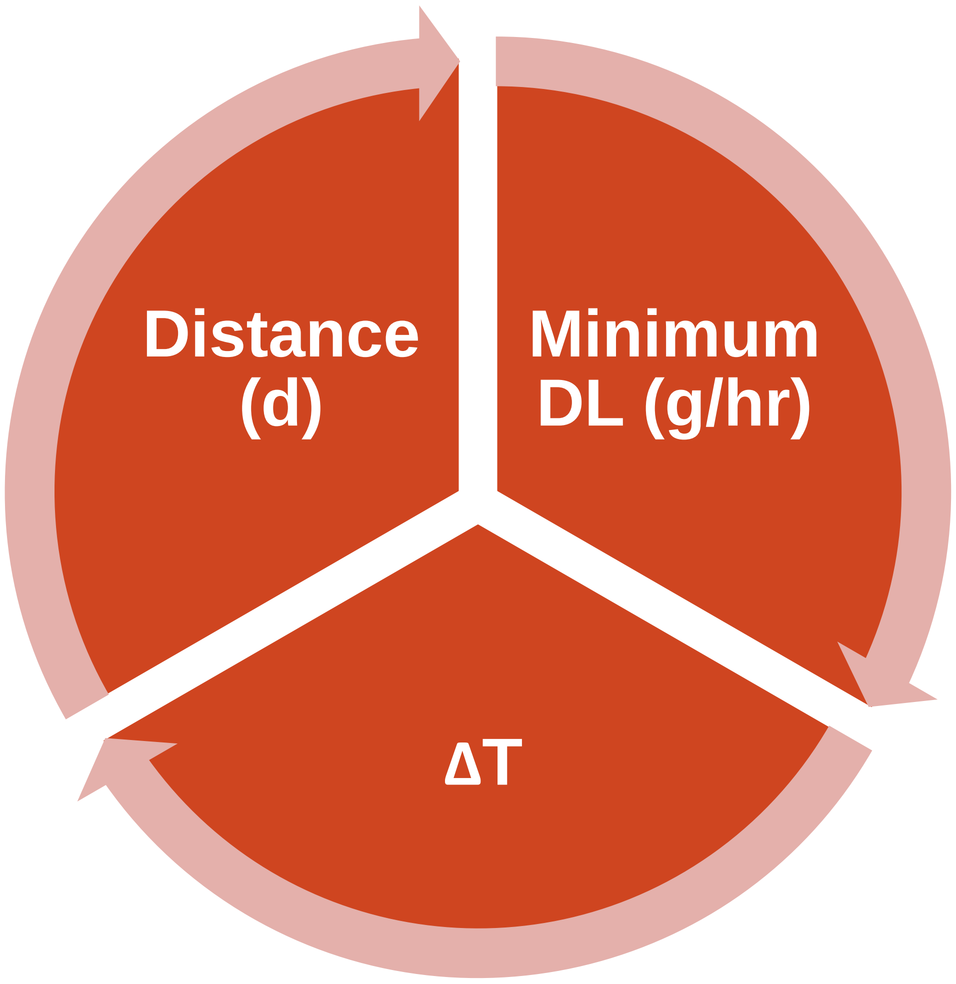


Red dash line is based on work by Ravikumar, et. al. [Ravikumar, A.P.; J. Wang, M. McGuire, C. S. Bell, D. Zimmerle, and A. R. Brandt, "Good versus Good Enough?" Empirical Tests of Methane Leak Detection Sensitivity of a Commercial Infrared Camera. *Environmental Science & Technology* 2018 52 (4), 2368-2374. DOI: 10.1021/acs.est.7b04945]

ERG Study for EPA

- In 2013-2014, ERG conducted a study for EPA in support of developing OGI protocol as Appendix K to 40 CFR Part 60 (http://www.regulations.gov/#!documentDetail;D=EPA-HQ-OAR-2010-0505-4949)
- The ERG study included over a hundred tests on OGI detection capability under controlled test conditions. With a few exceptions, the tests were done at a distance of 1.9 m (6.32 ft.) and ΔT was about 2 ^{O}C. The dividing line between "detect" and "non-detect" fluctuated between 6.4 and 16 g/hr. of propane/butane mixture.
- When the distance (6.32 ft.) and ΔT (2 ^{O}C) of the ERG tests are applied to Eq. 3, we get a detection limit of **11.3 g/hr**., which fits right into the range determined empirically by ERG study (**6.4-16 g/hr**.)

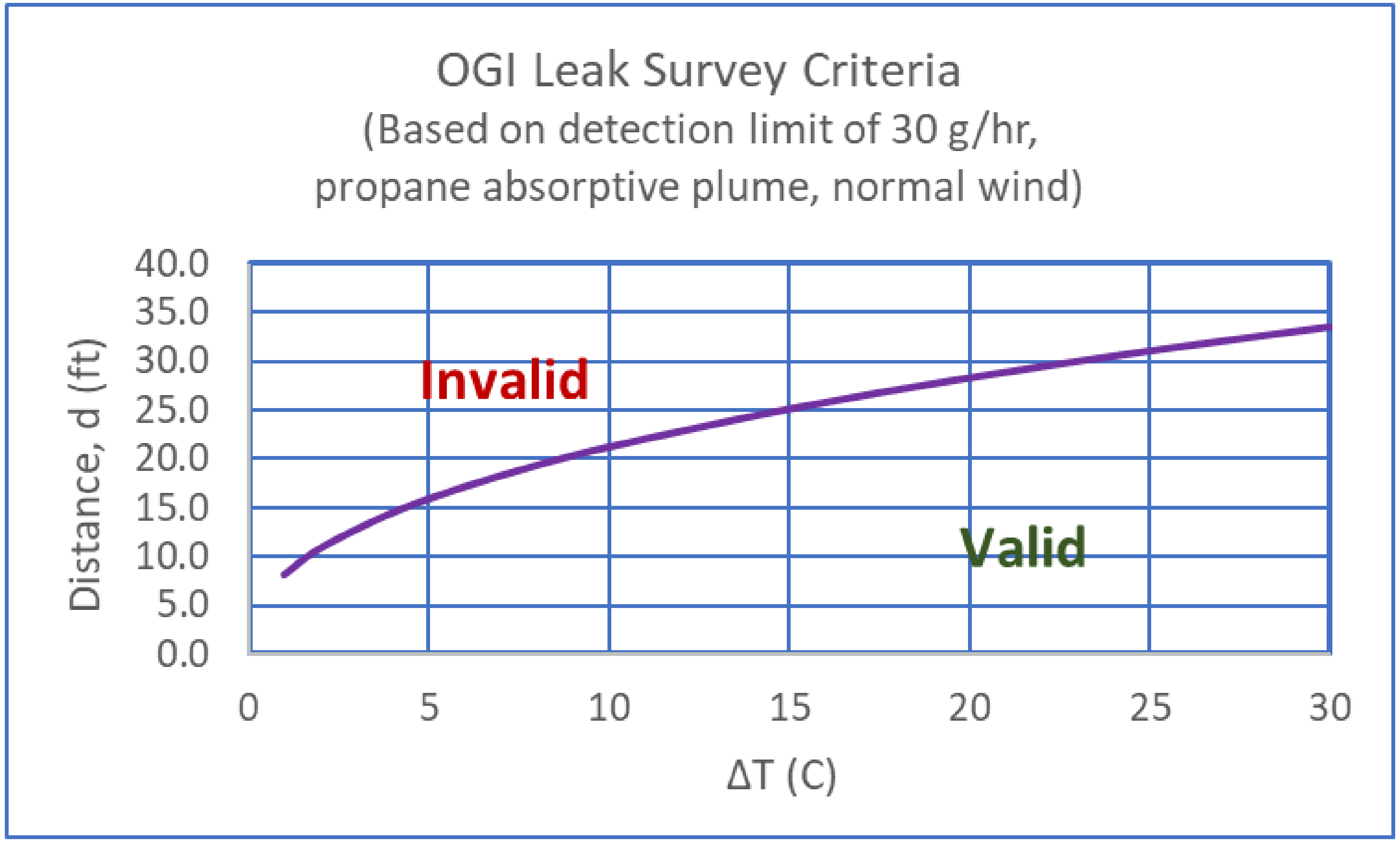
Key Factors for OGI Leak Survey Protocol



- Other factors
  - Type of OGI camera – Typically not a variable for a given camera
  - Gas composition – If a more refined approach is needed, use Response Factors
  - Dispersion conditions – Balancing the accuracy of the measurement and the challenge in measuring wind speed at extremely small spatial and temporal scales, a practical approach is to limit the leak survey conditions to exclude high wind conditions. Similar approaches have been used in Method 21.

Minimum ΔT and Maximum Distance d

- If a minimum detection level (g/hr) is set, the min. ΔT required and the max. distance (d) allowed can be established thru Eq. (3).
- An example chart shown on the right
- A higher ΔT will allow a greater distance while achieving the same desired detection limit.
- A shorter distance will allow a smaller ΔT for the same detection limit.



Tool to Ensure Minimum ΔT Requirement Is Met

- At a given distance, the OGI operator must ensure that the ΔT is >= the minimum ΔT required for desired detection limit (i.e. 30 g/hr).
- This can be easily accomplished for each background with a temperature-based screening tool
- Temperature screening addresses (and eliminates) the potential for a false negative result

Raw Image

Red areas below required ΔT at the given distance

Contribution of Equipment Leaks to Emission Inventory

- How do we quantify fugitive emissions for emission inventory or permitting when OGI is used as the sole leak detection method?
  - How do we estimate the contribution from the "non-detects"?
    - Issue: (Small leak rate per component) X (very large number of components) = fugitive emissions estimate
    - Current Method 21 based LDAR programs face the same issue. Industry is exploring similar approach for OGI, using emission factors for non-detect in OGI LDAR program.
  - In principle, a higher method DL → higher fugitive emission

$$\boxed{DL_{gph} = \mathrm{a} \cdot |\Delta T|^{-b} \cdot d^2}$$

  - For OGI, changing the minimum ΔT and/or the maximum distance allowed can lower the detection limit, thereby lowering the non-detect emission factor (analogous to lowering the leak definition from 1000 ppm to 200 ppm in Method 21 based LDAR)
  - The result may be that more leaks are detected, but the contribution from the "non-detect" will be lower, and the overall contribution from equipment leaks to the emission inventory will be lower.

Conclusions

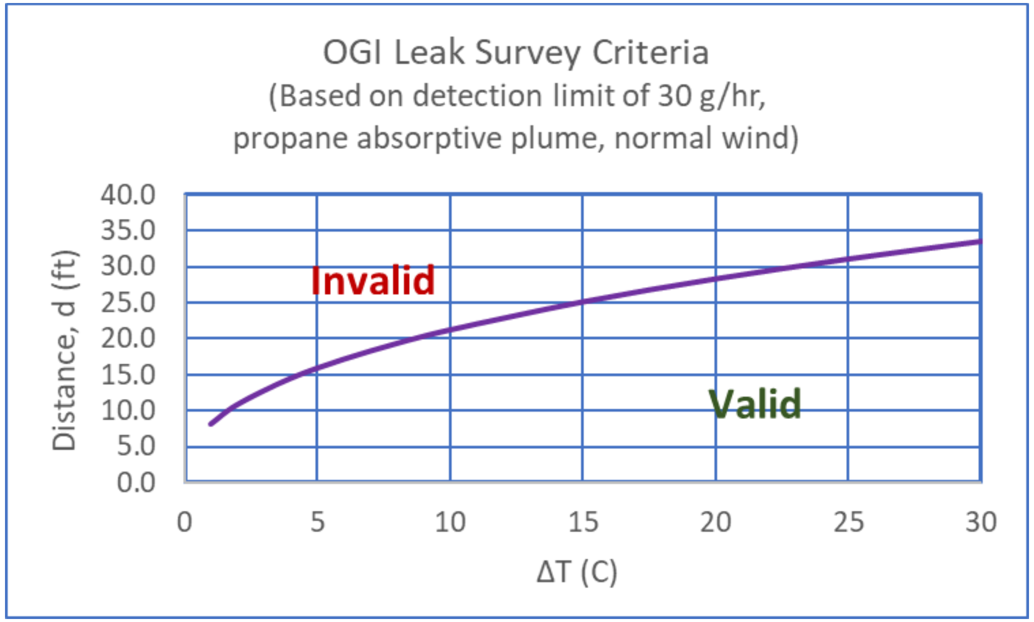
1. Two methods are presented for determining the DL of an OGI camera at the pixel level:
   a) NETD-based DL: ideal/lab-controlled conditions; suitable for camera spec comparison; impractical in most field conditions; analogous to "Instrument Detection Limit" (IDL)
   b) DL based on a higher threshold (e.g., 1% contrast, 3xNETD, etc.) will be more suitable in field conditions; analogous to "Method Detection Limit" (MDL)
   c) A $DL_{ppm\text{-}m}$ based on a different threshold can be derived by a ratio method. For example:
      i. Changing contrast threshold from 1% to 0.5% will yield a $DL_{ppm\text{-}m}$ = (1% contrast-based $DL_{ppm\text{-}m}$) x (0.5%/1%)
      ii. Changing threshold of ΔT_g = NETD to ΔT_g = 3xNETD will yield a $DL_{ppm\text{-}m}$ = (NETD-based $DL_{ppm\text{-}m}$) x 3

2. For a given OGI camera, OGI detection limit in terms of emission rate is influenced primarily by ΔT and distance

$$\boxed{\boldsymbol{DL_{gph}} = \mathbf{a} \cdot |\boldsymbol{\Delta T}|^{-\boldsymbol{b}} \cdot \boldsymbol{d}^{2}}$$

Conclusions

3. OGI DL will affect its equivalency to current LDAR programs and emission inventories when OGI is solely used for fugitive emission sources (due to emission rate assigned to non-detects).
4. For ~240 gases (many of them are common in downstream facilities), an uncooled OGI camera may be comparable to a cooled camera, but at lower cost.
5. OGI detection limits vary with environmental conditions and leak survey protocols. However, a combination of min. ΔT and max. distance will ensure that an LDAR program based solely on OGI will achieve the same or better results as a conventional LDAR program (Method 21)



Thank You!

Yousheng Zeng, PhD, PE | CEO
youshengzeng@providencephotonics.com

Jon Morris | CTO
jonmorris@providencephotonics.com

+1 833 746 8664 | WWW.PROVIDENCEPHOTONICS.COM