DAS技術介紹與經驗分享

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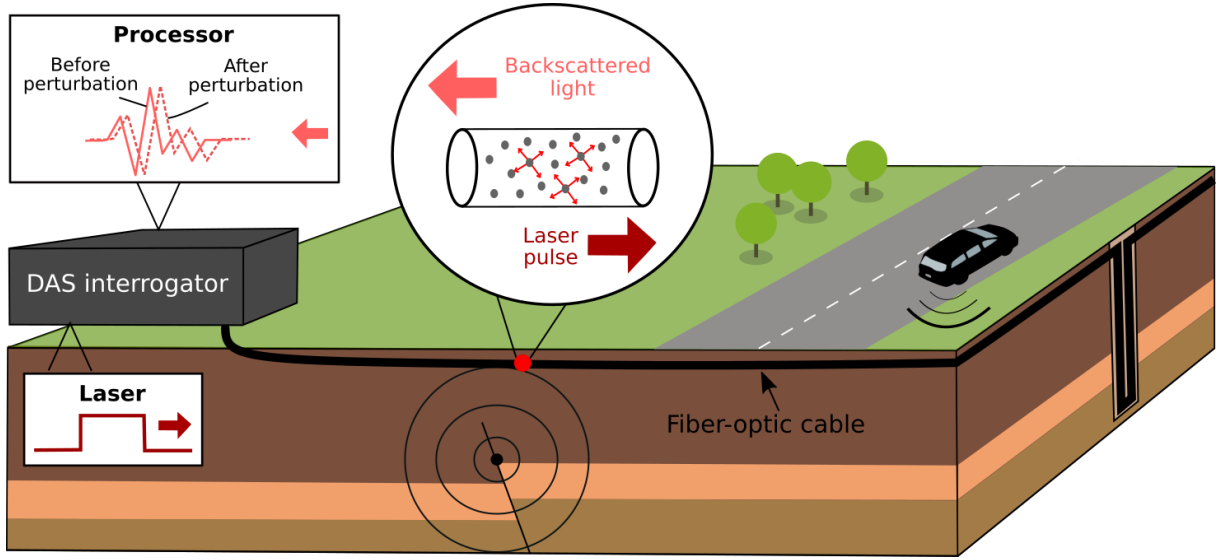
IES

DAS
(Distributed acoustic sensing)

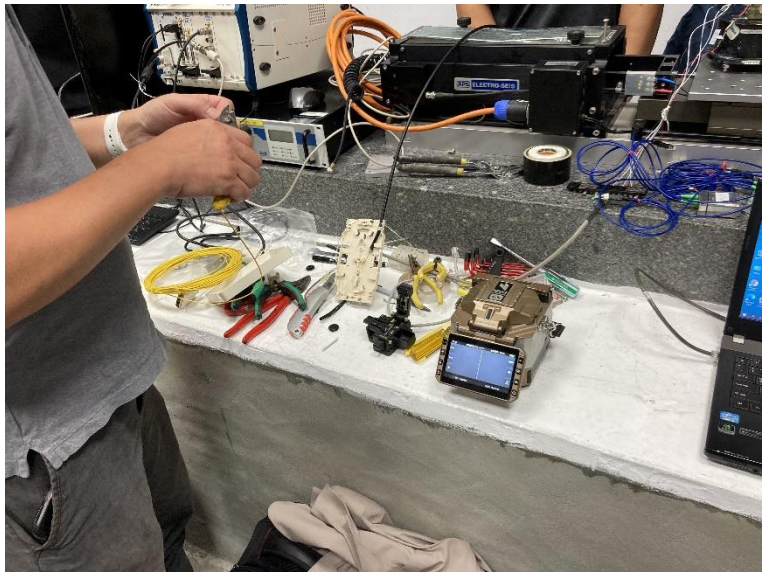
DAS measures axial strain or strain-rate along fiber cable, while seismometer measures 3-component velocity or acceleration.

Linear array measurement

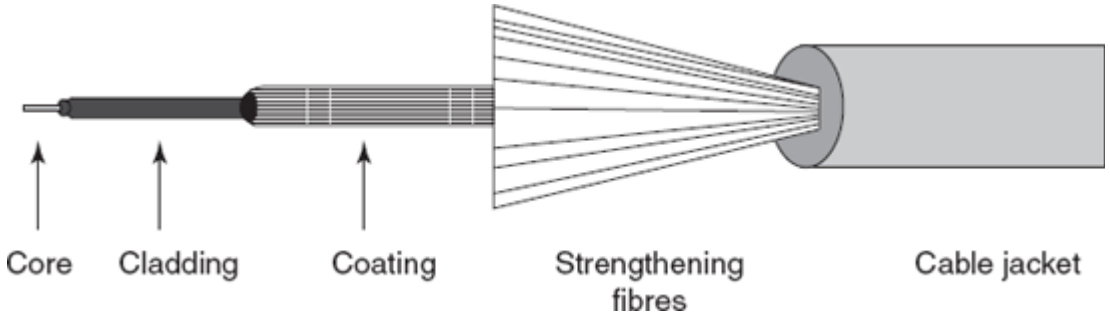


Ground motion measurement

Fiber cable knowledge

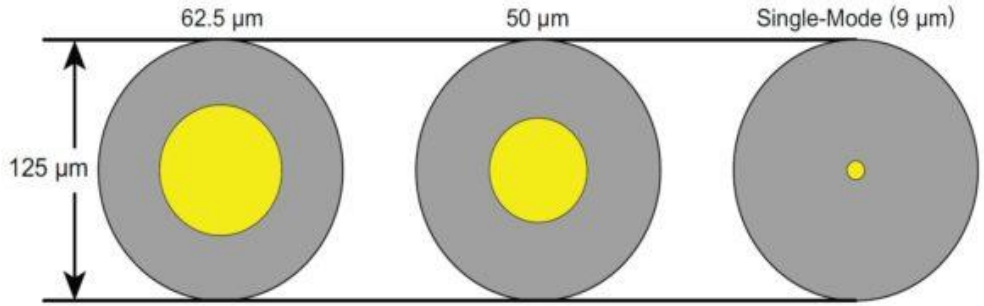


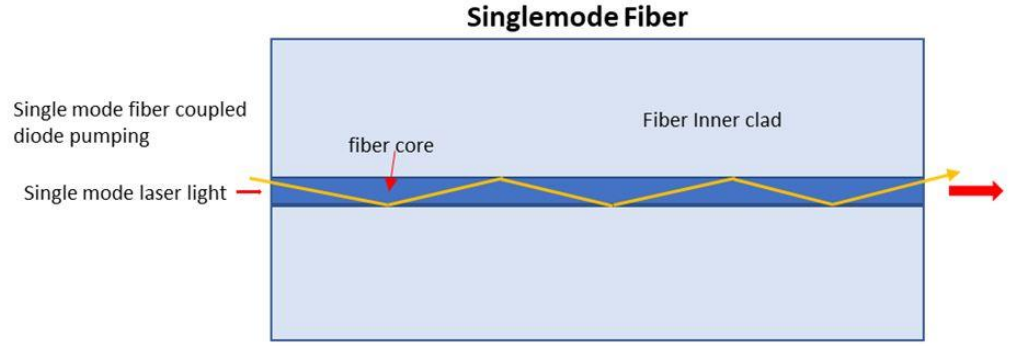
Fiber-optic cable construction

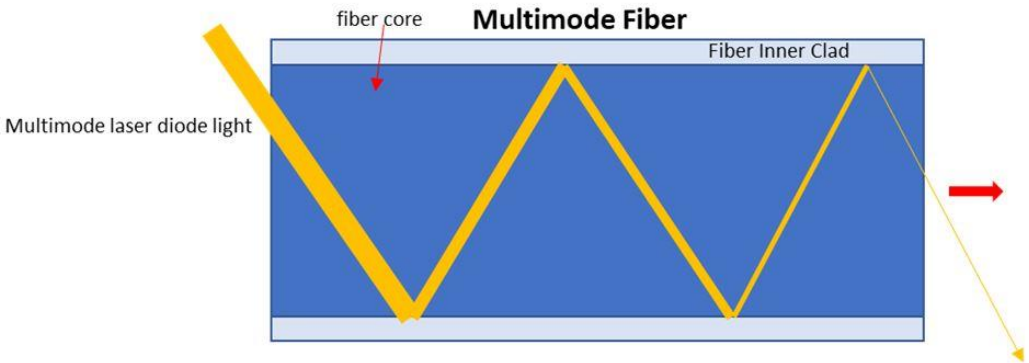


Optical Fiber Core Diameters

Relative Size Comparison







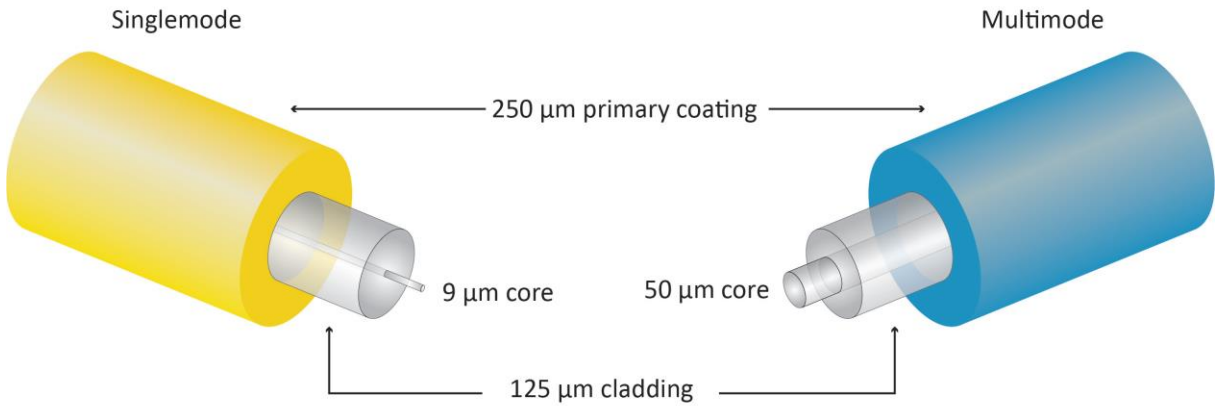
光纖可分為三層：核心、包層和塗層。
核心和包層一般由石英（sio2）組成，塗層由特殊塑膠組成
核心折射率高於包層

Single-Mode Fiber 單模	Multimode Fiber 多模
8.3 μm in core diameter	50 or 62.5+ μm in core diameter
Utilizes expensive laser light	Generally uses cheap light-emitting diode light source
Light travels in a single path down the core	Multiple paths used by light
Long distances, >5 miles	Short distances, <5 miles
波長較長，主要為1310nm與1550nm	波長較短，為850nm和1300nm
DAS	DTS

光纖線纜
silica (SiO2) glass

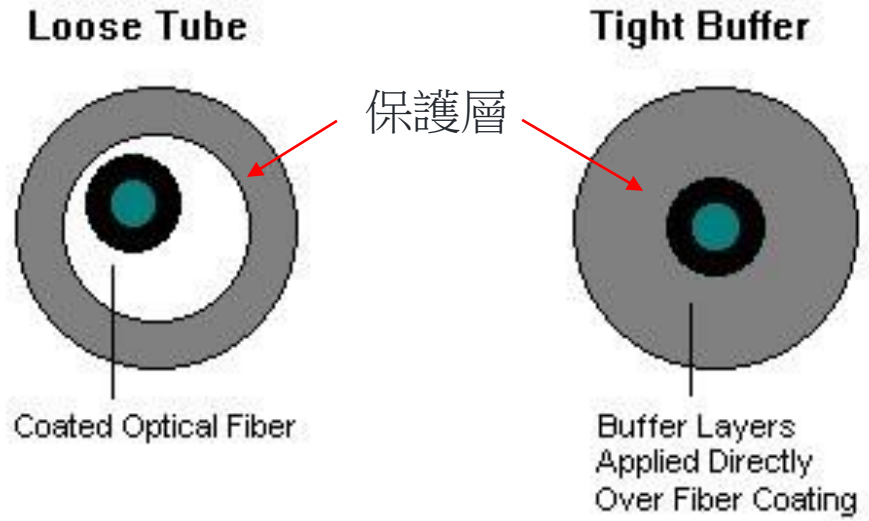
單模
形變 (strain)
DAS

多模
溫度 (temperature)
DTS



Primary coating ambient temperature range

Acrylate	-40°C to +85°C
HT Acrylate	-40°C to +180°C
Silicone PFA	-40°C to +200°C
Polyimide	-180°C to +300° C
Metal	-250°C to +650°C



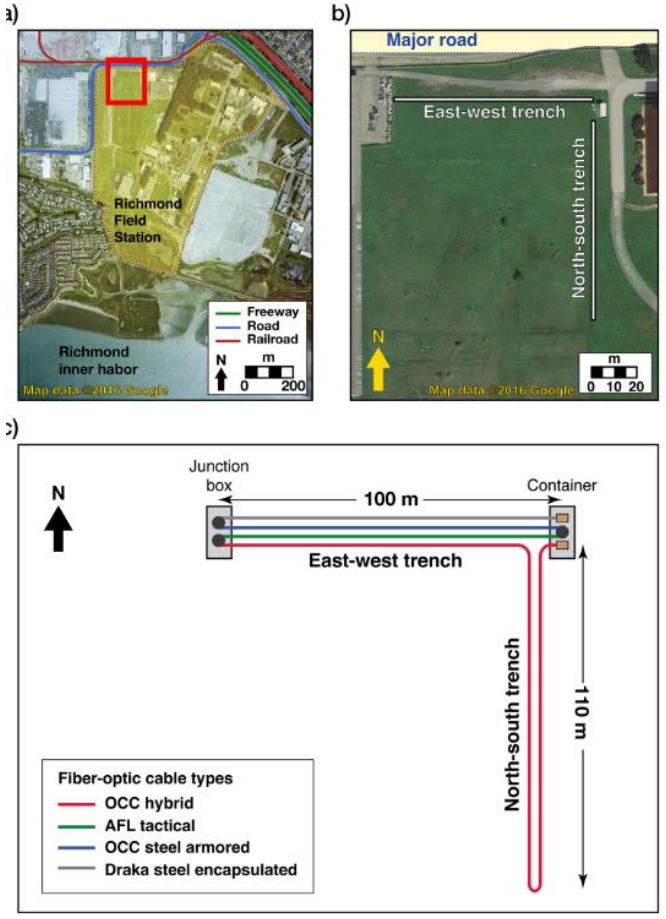
光纖結構

鬆套管(Loose Tube)：戶外和長距離應用，提供了更好的保護光纖免受環境損害，有充膠或無膠的設計，膠是為了避免水氣

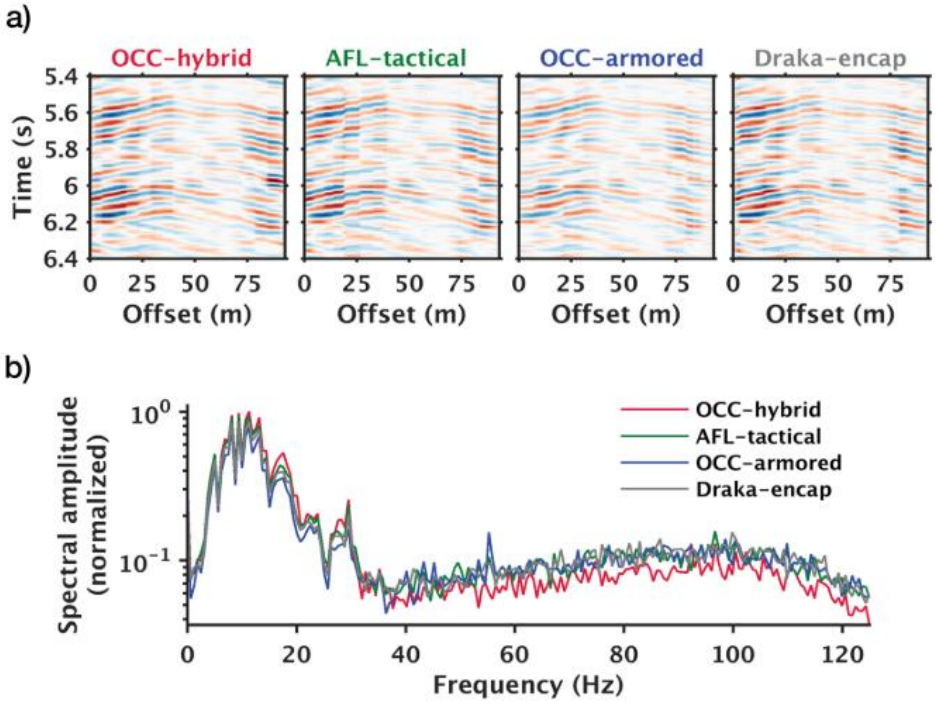
緊包覆層(Tight Buffer)：室內和短距離應用，更容易連接和插拔

Different cable packing

The trenches were 50 cm deep



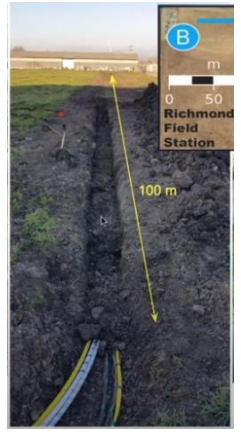
[Shan Dou, et. al., 2017]



Jonathan Ajo-Franklin

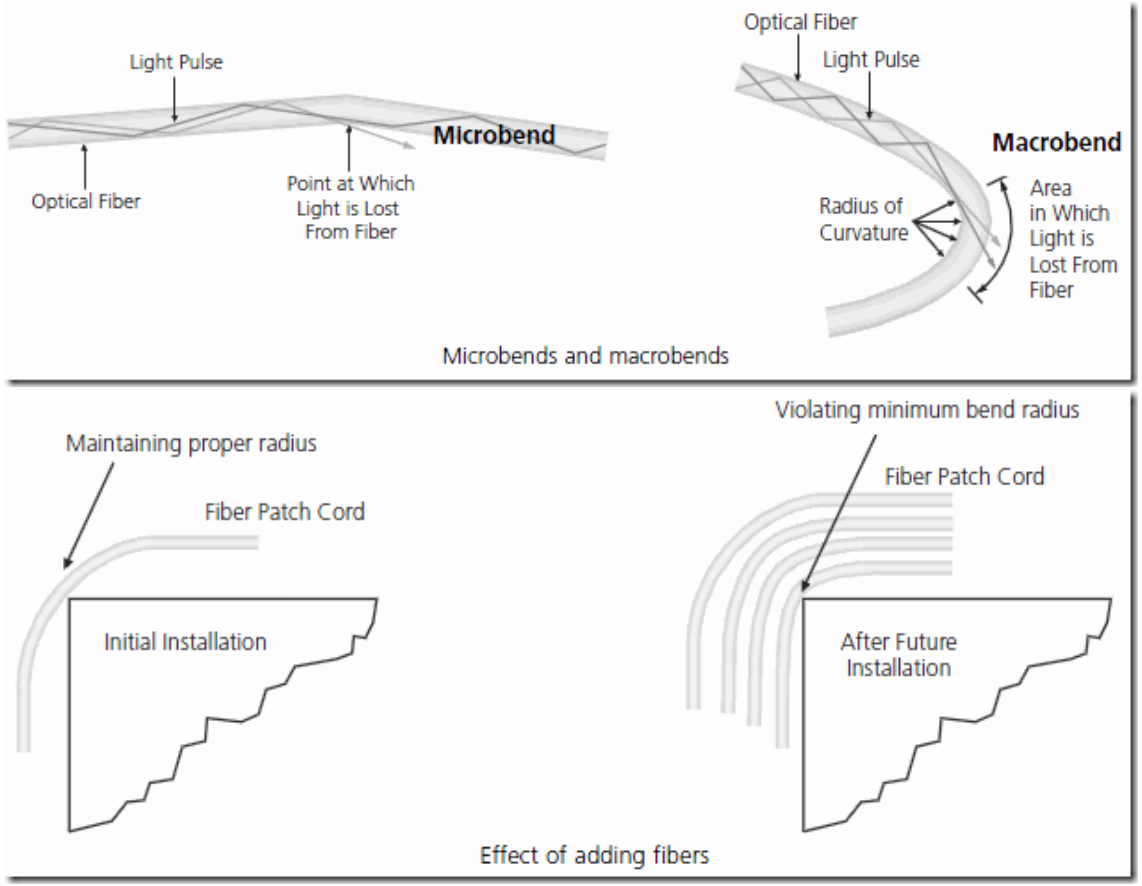
The influence of cable packaging on DAS sensitivity is minor. Similar signals with different fibers f ~ 0.5-50 Hz

- a gel-filled, polyethylene-coated hybrid cable (OCC hybrid)
- a tight-buffered, polyethylene-coated tactical cable (AFL tactical)
- a gel-filled, steel-armored cable (OCC armored)
- a tight-buffered, steel-tubing encapsulated cable (Draka encapsulated)

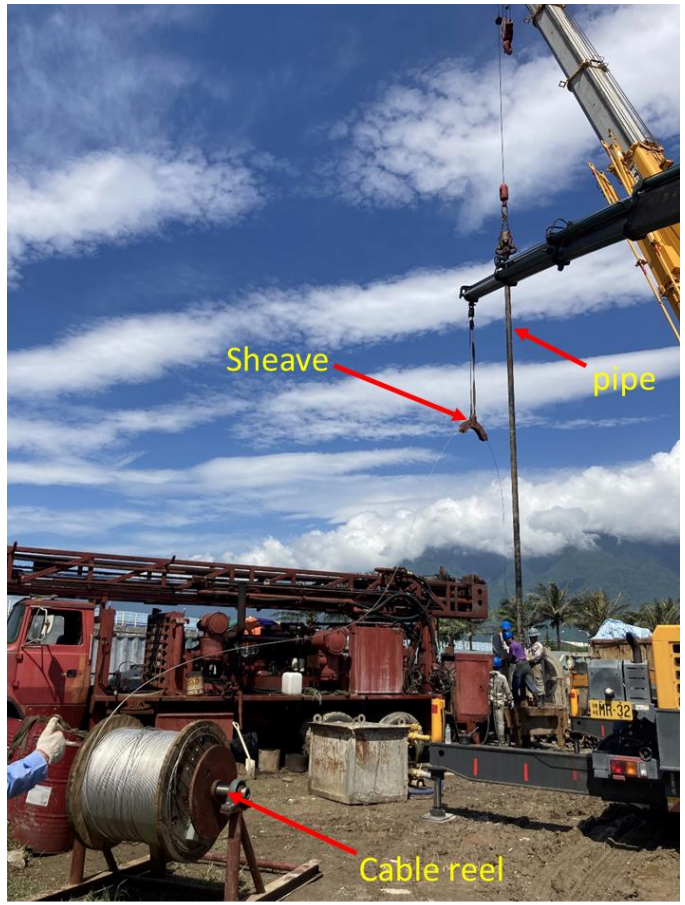


FIBER OPTIC BEND RADIUS PROTECTION

in general, the minimum bend radius should not be less than ten times the outer diameter (OD) of the fiber cable. Thus a 3mm cable should not have any bends less than 30mm in radius.



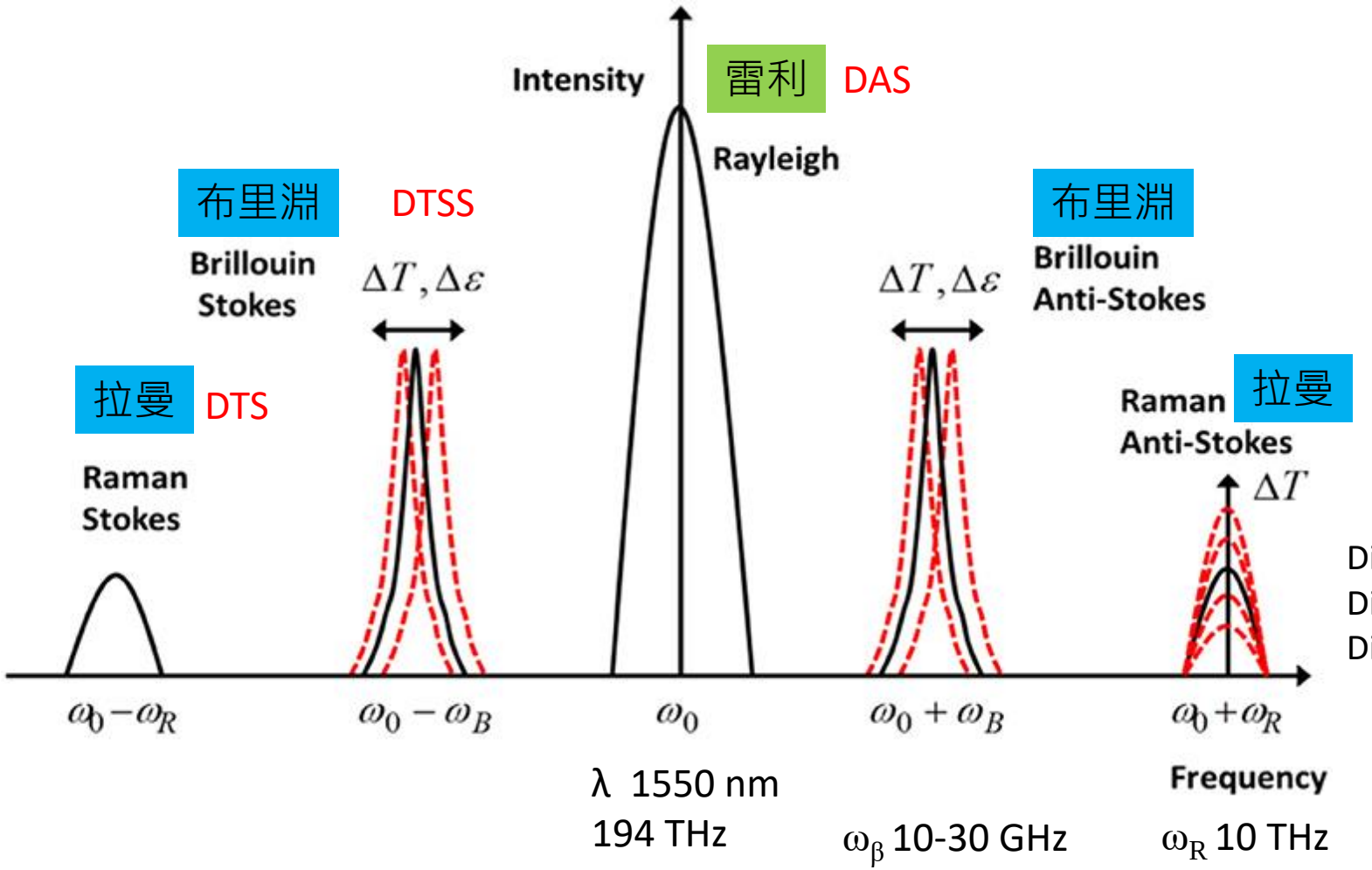
https://www.fiberoptics4sale.com/blogs/archive-posts/95051526-fiber-optic-bend-radius-protection



散射(scattering)

彈性散射與非彈性散射:光的波長（頻率）是否發生改變

非彈性散射能量較低



λ 1550 nm
194 THz

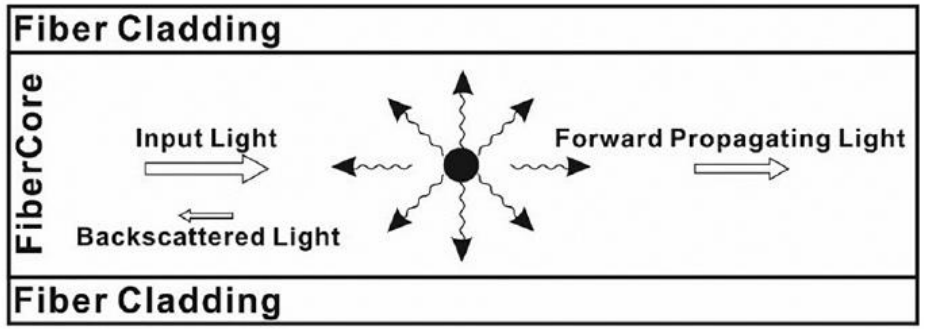
ω_β 10-30 GHz

ω_R 10 THz

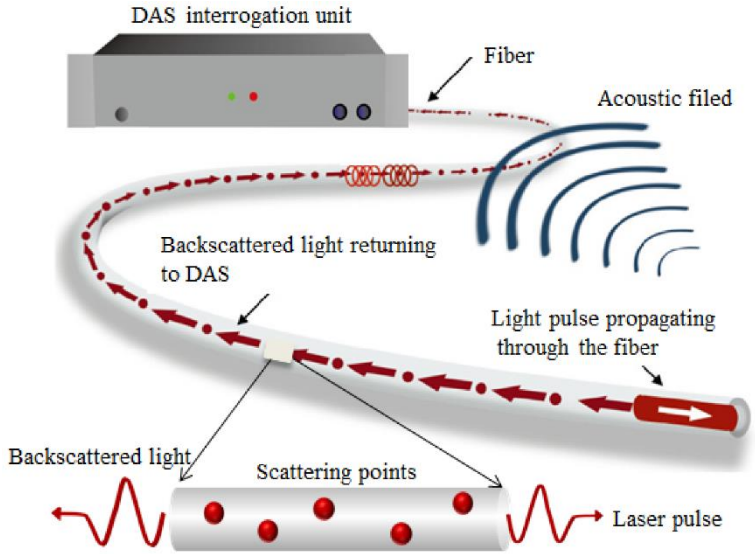
the Anti-Stokes band arises when energy is transferred from the medium to the light, leading to scattered photons at a higher frequency than that of the incident light

Distributed acoustic sensing (DAS)
Distributed Temperature and Strain Sensing (DTSS)
Distributed temperature sensors (DTS)

DAS原理



taken from (Lu et al., 2019)



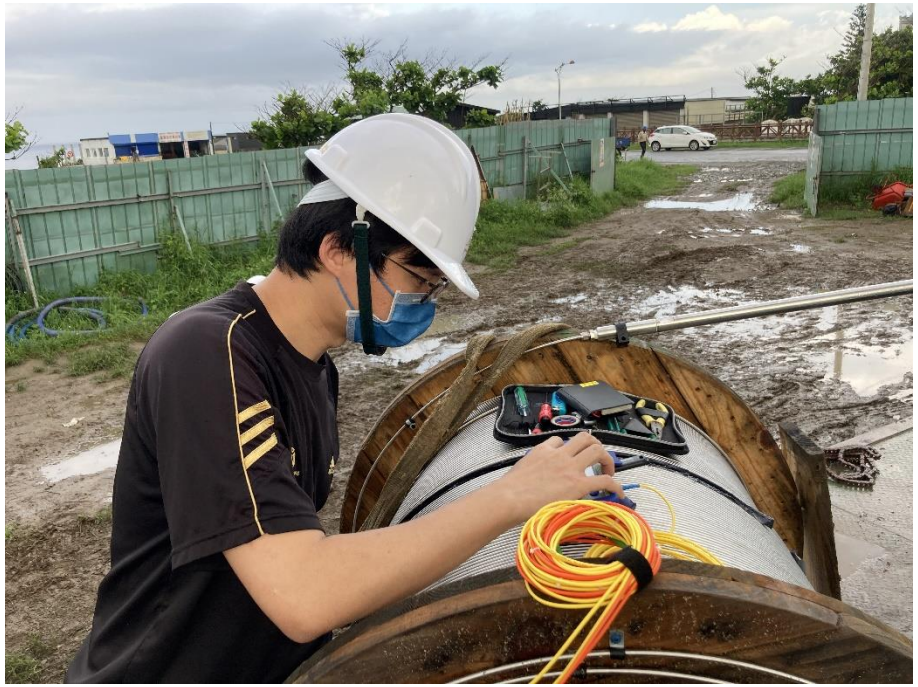
- DAS儀器接上單模光纖，送出波長1550nm的雷射脈衝，沿途經過光纖線製造過程的雜質，產生Rayleigh scattering，並回返到DAS儀器，散射傳遞的時間與散射發生的位置成正比，因而DAS有空間辨識能力。
- DAS每發射一次雷射脈衝，需等待雷射脈衝走到線纜的最後，才會再次發射，因此光纖線纜長度決定了時間取樣率/解析度。(50Km光纖線取樣率2000Hz)
- 雷射脈衝越寬(100 ns pulse giving 10 m)，散射的光能量越強，也因此可以傳送越遠的距離，但也導致較差的空間解析度
- DAS 基於Rayleigh scattering，輸入的頻率與散射的頻率相同，DAS同時對strain與溫度都敏感，但溫度影響在長週期，可和strain分離。儘管對溫度敏感，但不像Brillouin or Raman scatter可得到絕對溫度，DAS只能得到溫度變化
- The optical phase change ΔΦ is proportional to the elongation of the fiber (ΔL) over the gauge length (L).
- DAS waveforms obtained at each channel are not a point measurement but are strains measured over a spatial distance.

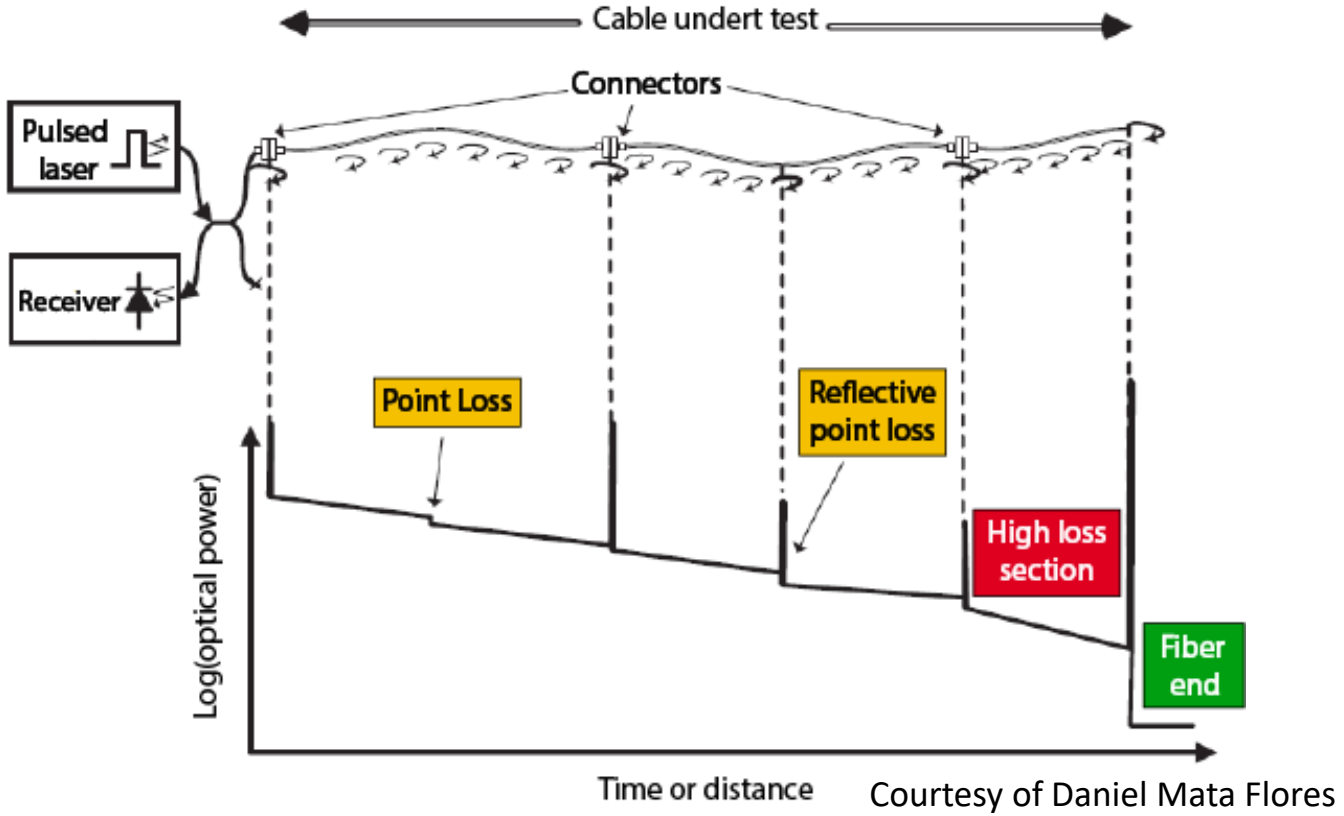
Linearity between phase change to strain

$$\varepsilon = \frac{\lambda}{4\pi n L \xi} d\phi$$

ϕ: optical phase
n: refractive index (1.445)
k: incident wavenumber
L: Gauge length
λ: incident wavelength (~1550 nm)
ξ: scalar multiplicative factor (~0.78) (0.735)

OTDR 檢測光纖線品質
(Optical Time-Domain Reflectometry)



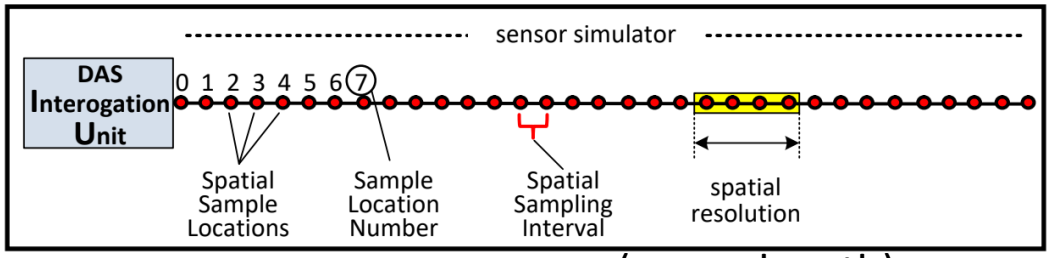


Courtesy of Daniel Mata Flores

- initially proposed in the late 1970s to monitor the operational health of optical transmission lines
- By analyzing the amplitude of the Rayleigh backscattered signal of a high-power light pulse propagating along the fiber, OTDR detects attenuating/reflective faults or imperfections in the cable

DAS (Distributed Acoustic Sensing)

光速 $3*10^8$ m/s
光纖長度 100 km
資料取樣率 $2/3*10^{-3}$s



(gauge length)

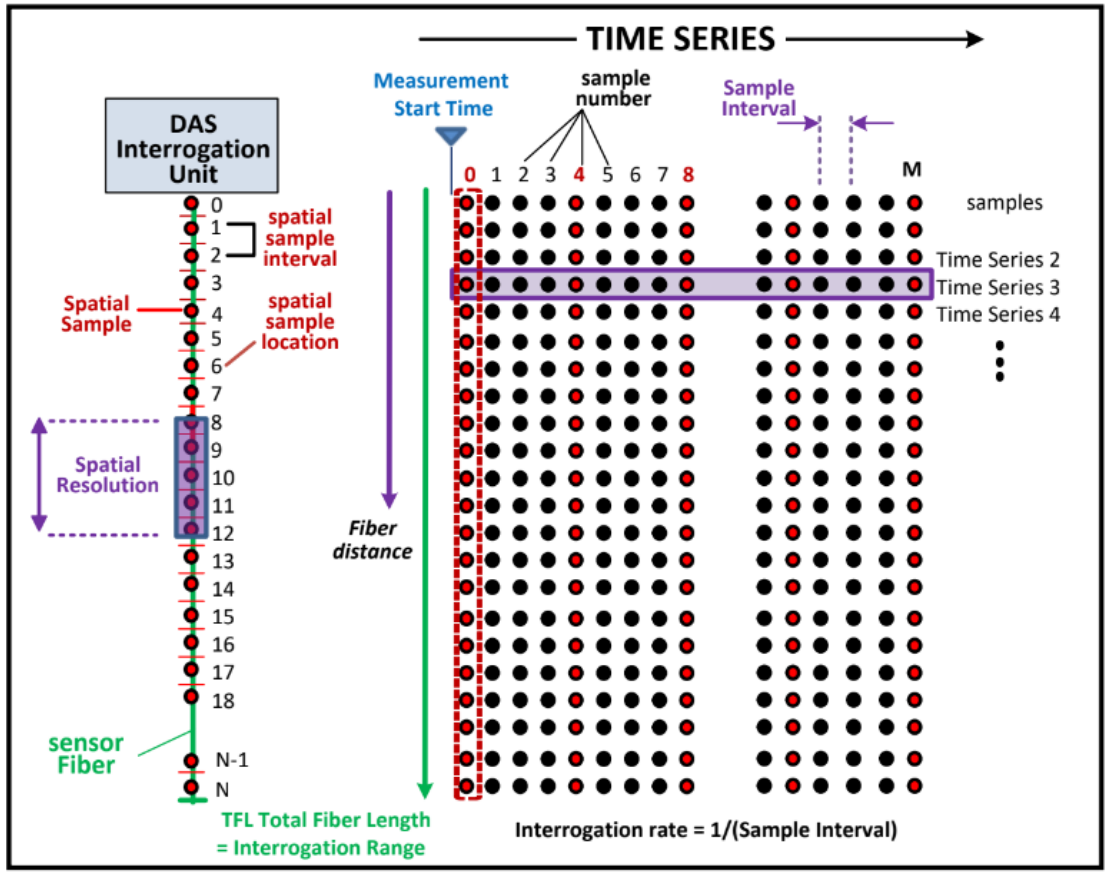


Figure 3. Signal Parameters relating to Time Series and their Spatial Location Identification

Spatial sampling (gauge length) vs. Spatial resolution

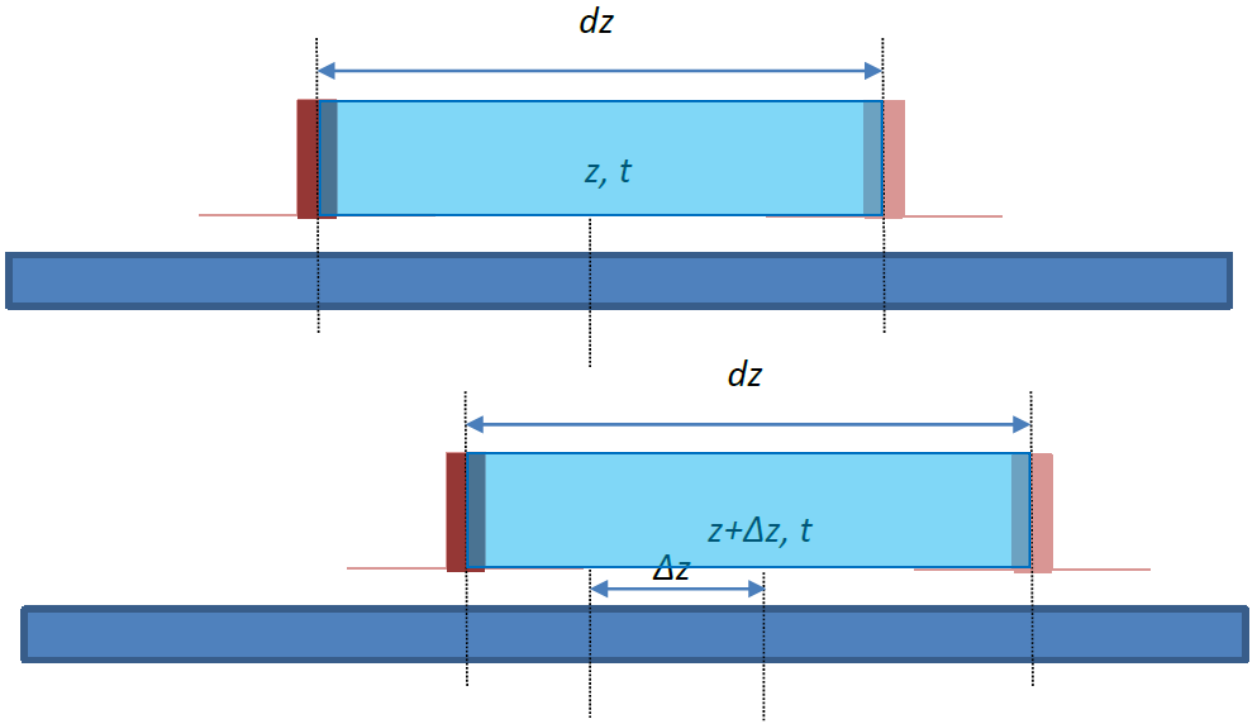


Illustration of two spatially-consecutive iDAS measurements, at *z, t* and *z+Δz, t*. *dz* is the gauge length, which is generally larger than the sampling resolution, *Δz, the distance between consecutive measurement points*

From Silixa

sampling resolution ***Δz*** : It is the distance between two adjacent sampling points along the fibre in the data saved to disk.

gauge length dz : The iDAS interrogator measures, in a moving window, the relative strain between two sections of the fibre that are separated by a length dz. The gauge length and spatial resolution have the same value to a good approximation

DAS waveforms obtained at each channel are not a point measurement but are strains measured over a gauge length sized window.

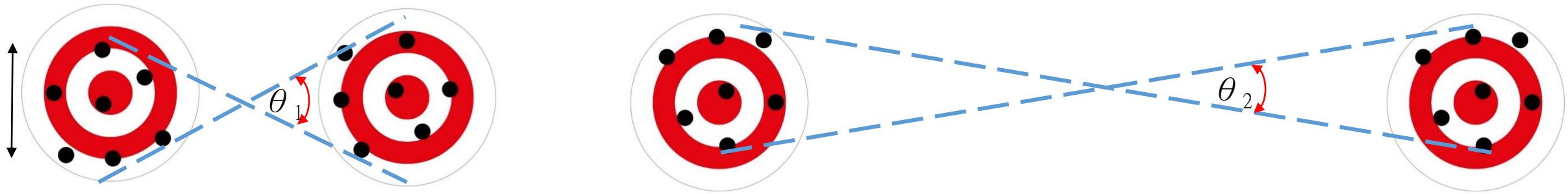
a large gauge length improves the SNR but reduces the measurement resolution

The gauge length (GL) is often expressed as a multiple of the sampling resolution (SR): GL = N · SR, usually with N > 4.

How gauge length relates with resolution?

Larger the gauge length, better the resolution

$\theta_1 > \theta_2$

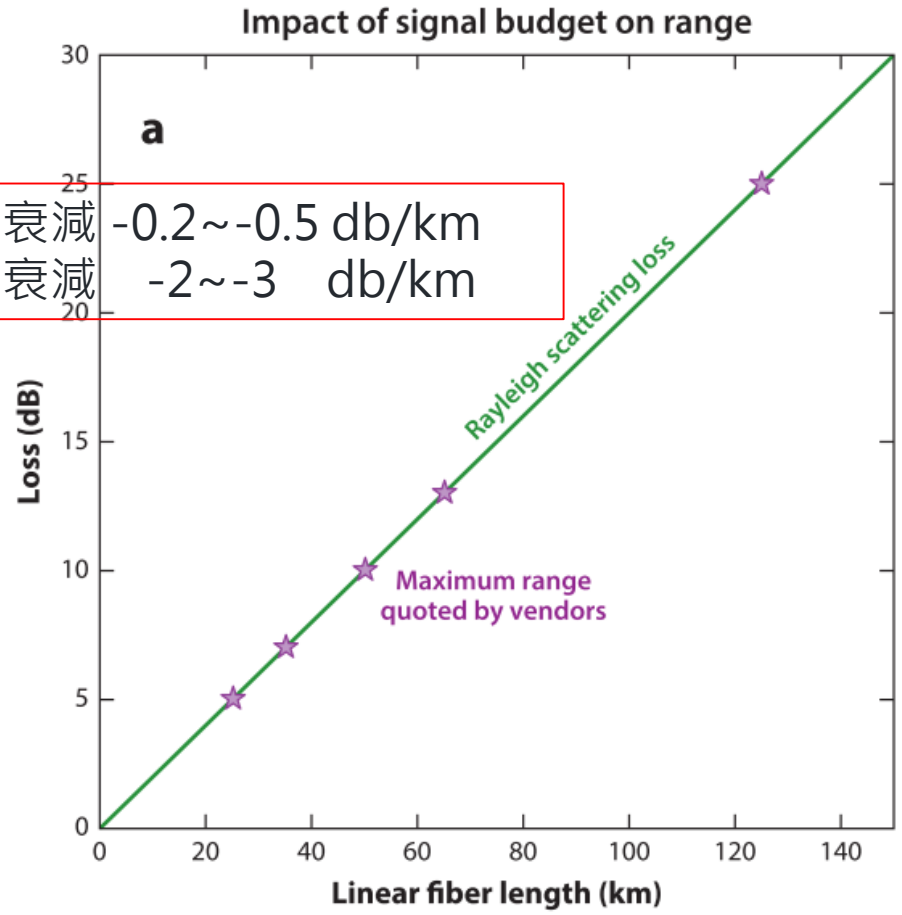


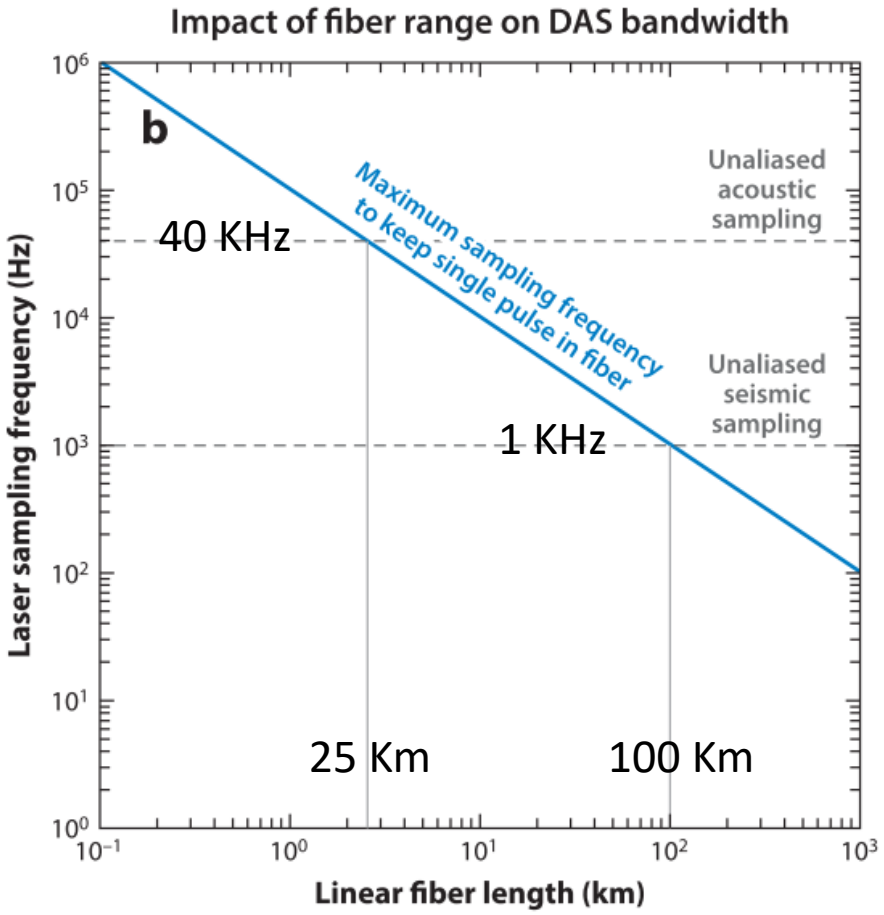
Optical noise range

DAS current length limitation

DAS每發射一次雷射脈衝，需等待雷射脈衝走到線纜的最後，才會再次發射

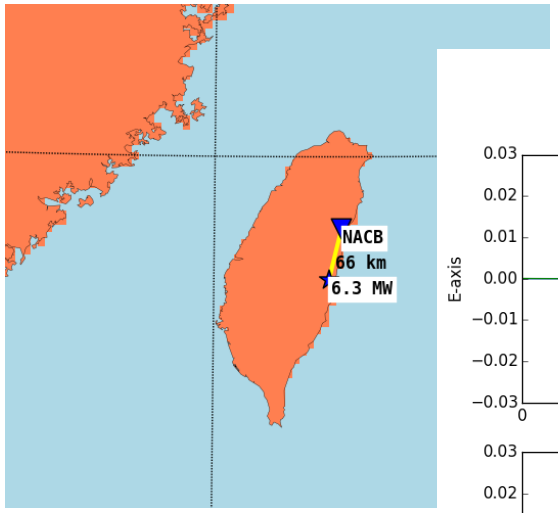
單模光纖的衰減 -0.2~-0.5 db/km
多模光纖的衰減 -2~-3 db/km

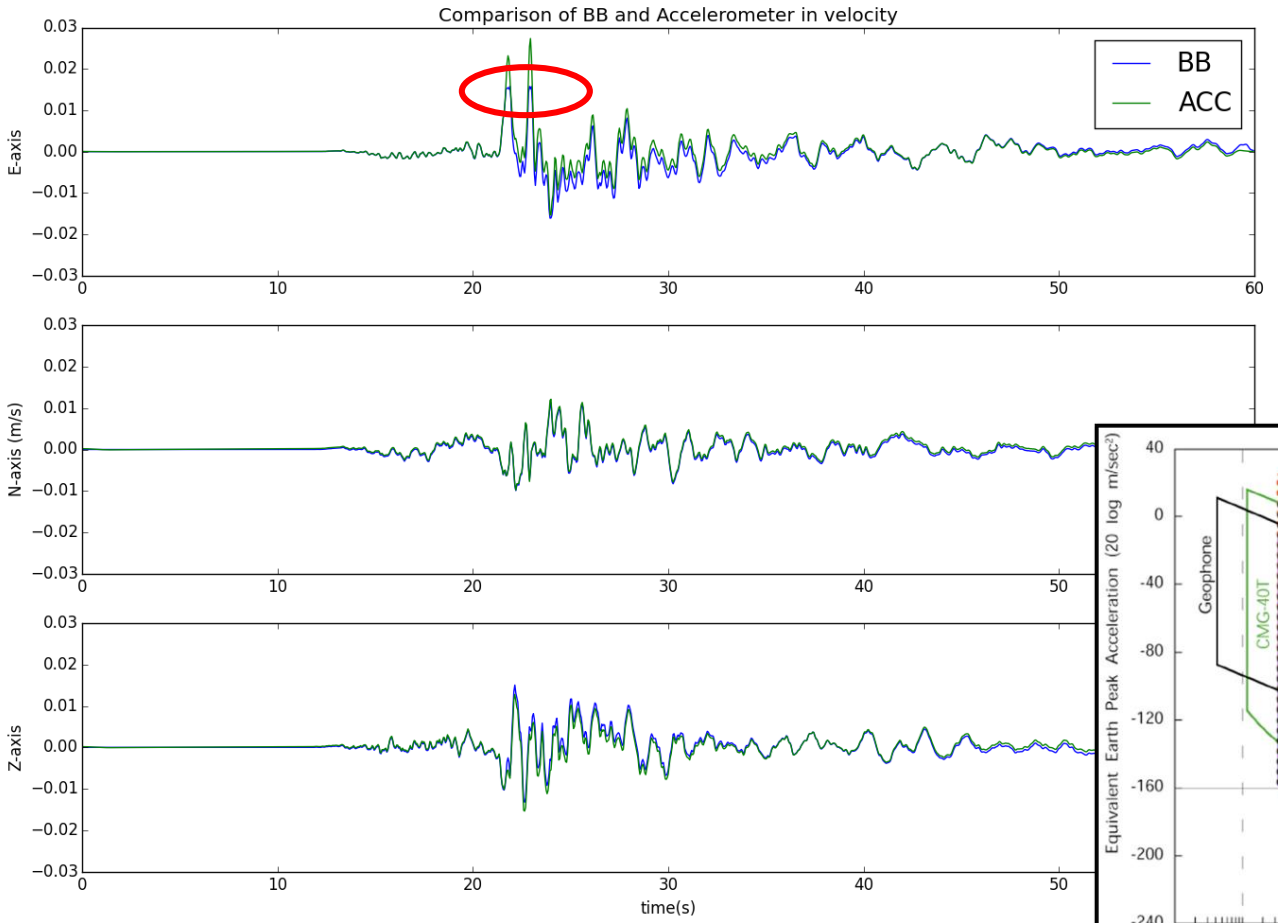




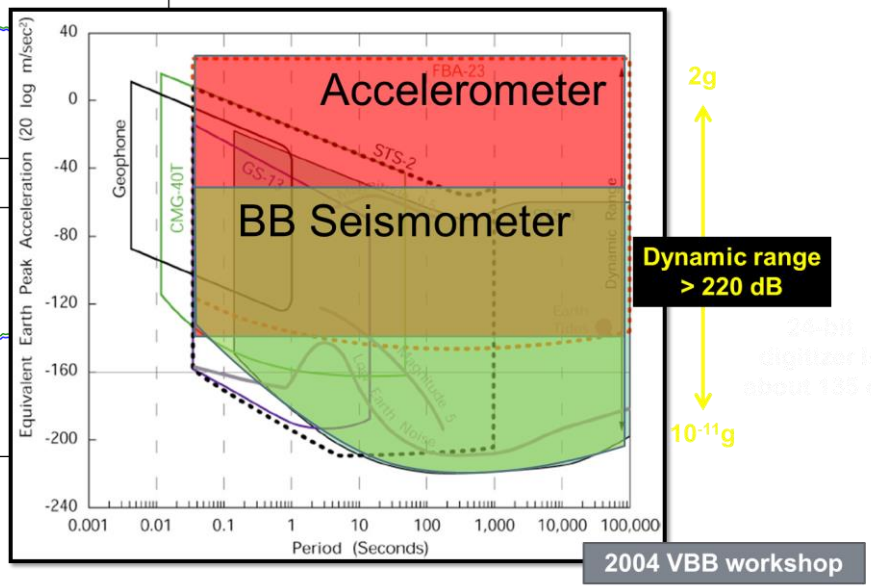
[Lindsey and Martin, 2021]

“Clipping” of seismometer





due to dynamic range limitations of the sensor or digitizer



DAS資料飽和現象(data saturation)

- The DAS IU we utilized returns the wrapped phase in the range (−π, π), and when the strain rate exceeds 2π between sample points, the signal is saturated.

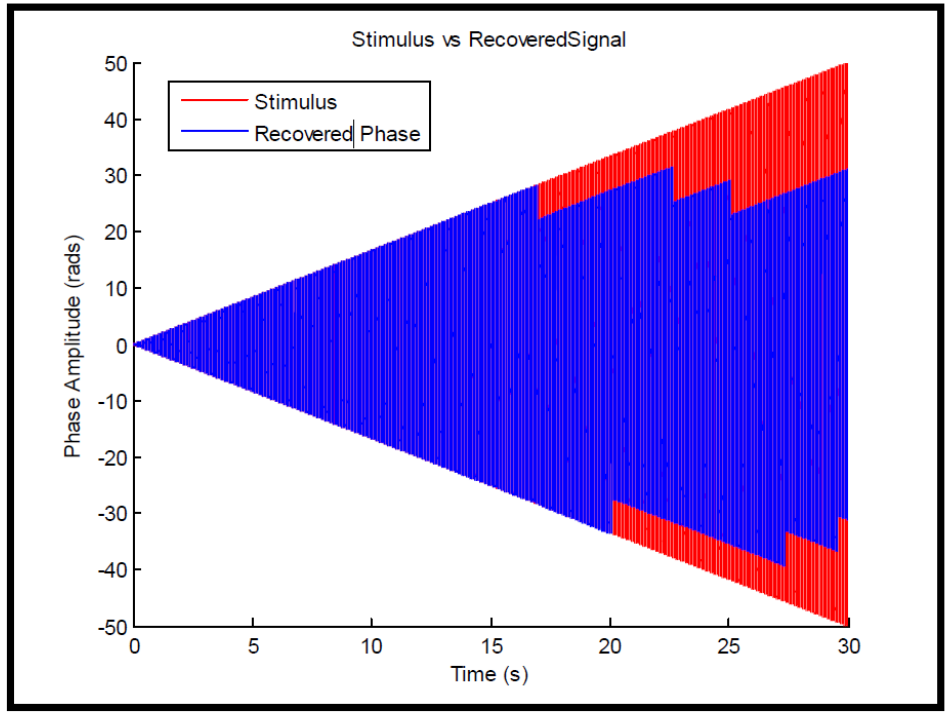


Figure 20. Stimulus signal (red) and IU response (blue) showing linear limit at 17 seconds

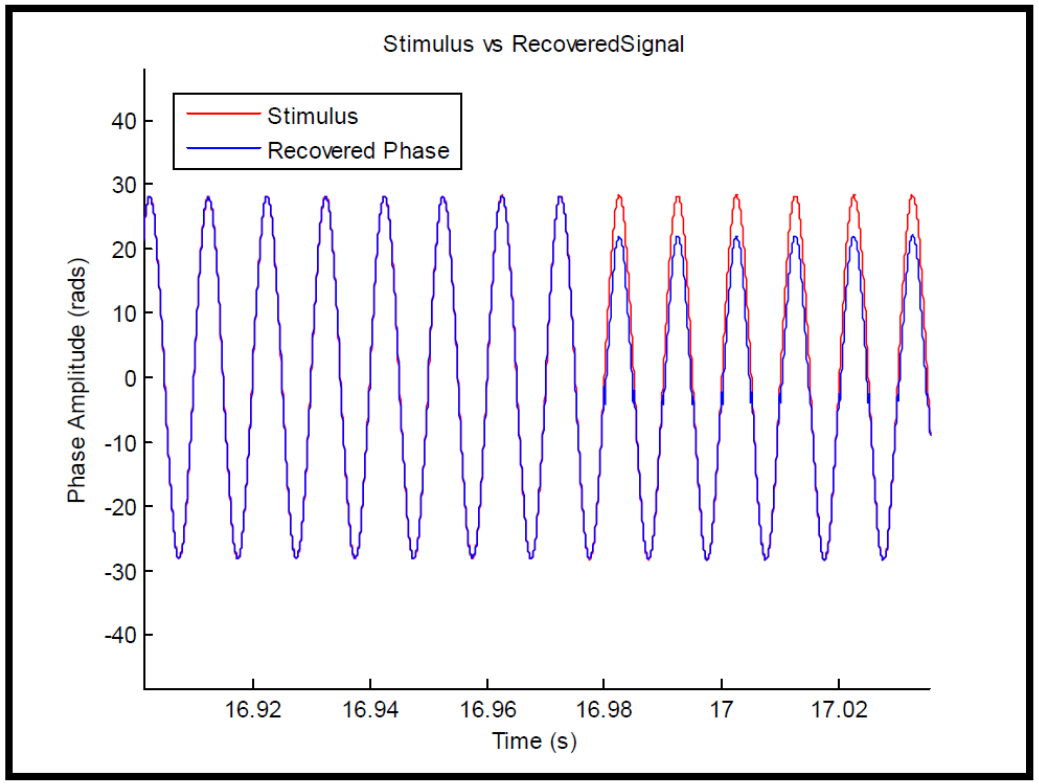
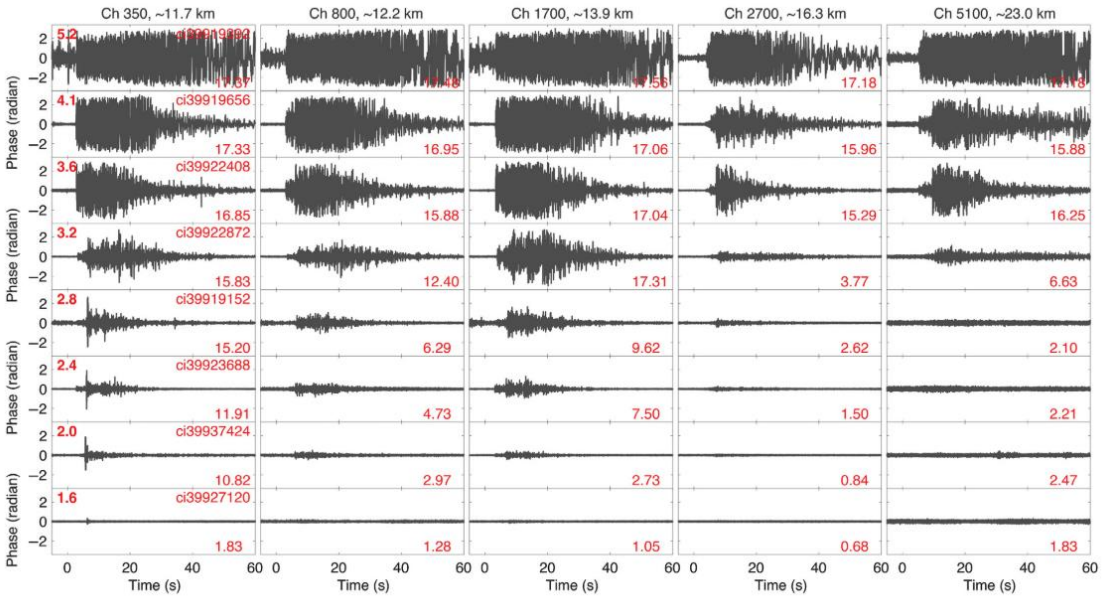


Figure 21. Zoom view of stimulus signal and IU response showing phase jump at 16.98 seconds

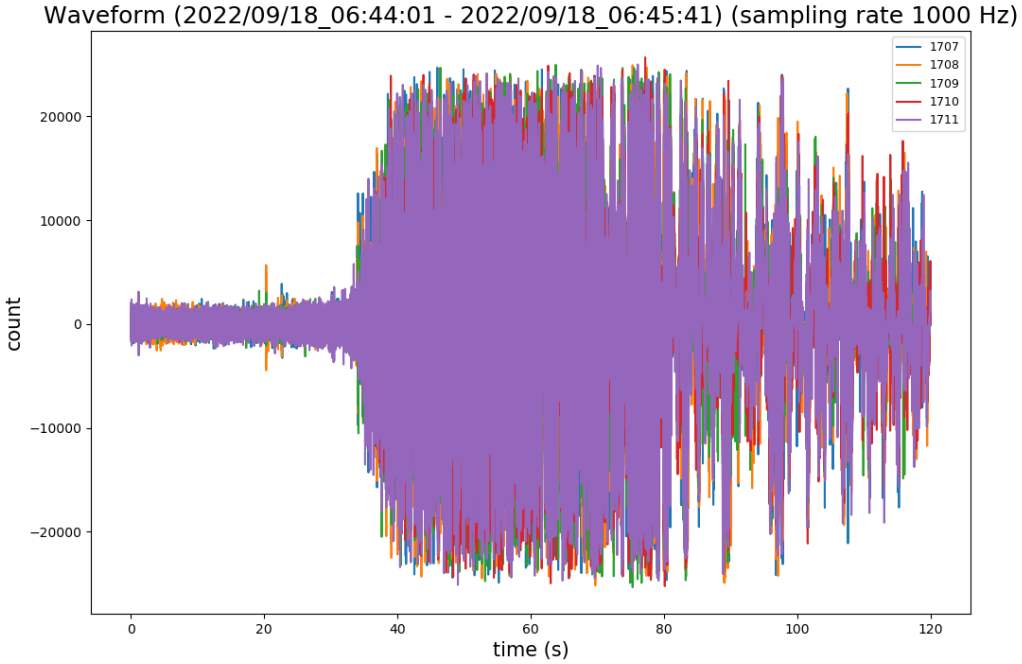
[SEAFOM]

Das data saturation

Increase internal laser repetition rate or shorten the gauge length both increase DAS saturation level. The maximum laser repetition rate is in turn constrained by the total fiber length because the detector must wait for returning scattered energy before launching a new pulse at the same wavelength. Shorten gauge length also increase instrument noise.



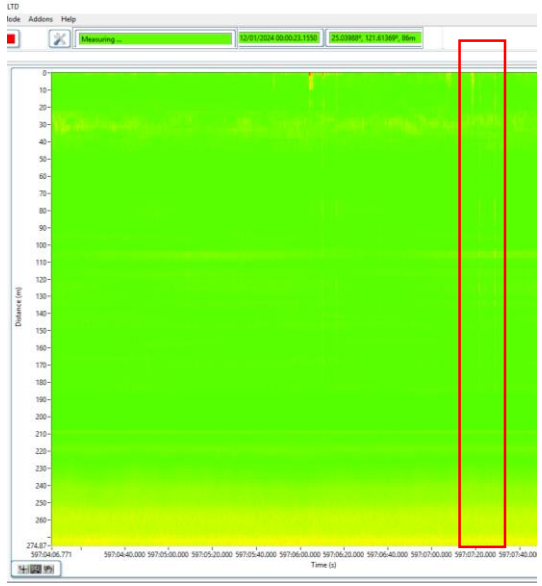
[The Imperial Valley Dark Fiber Project: Toward Seismic Studies Using DAS and Telecom Infrastructure for Geothermal Applications]



MiDAS (surface B data)

隔震桌

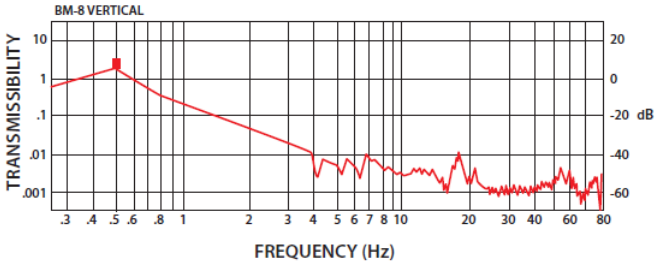
Minus K® model 75BM-8

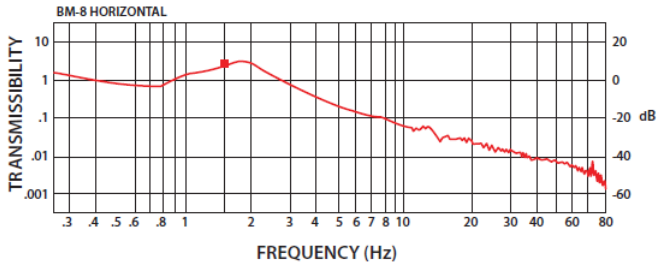


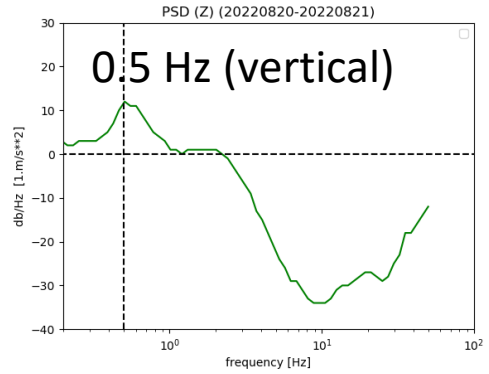
common-mode noise is characterized by an infinite-velocity signal (arrives at all channels simultaneously). This is caused by local seismic disturbance near the interrogator, which vibrates the optoelectronic system and leads to an overprinted signal on all channel recordings at the same time. [Lindsey et al., 2020]

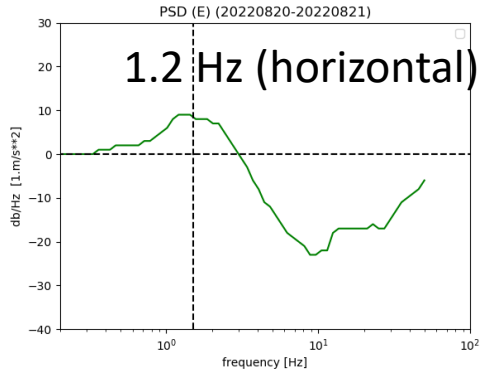
Typical Performance Curves:

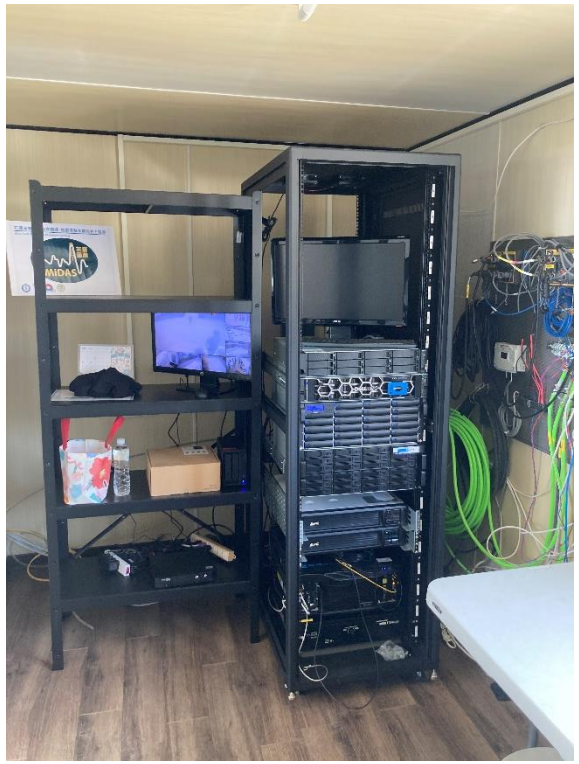
much better than typical air tables.





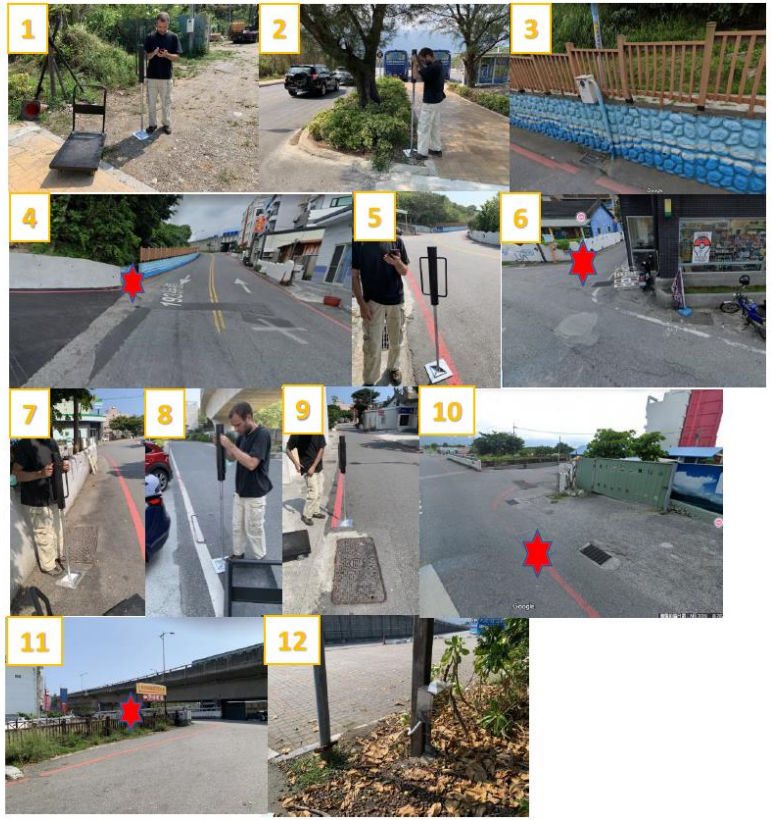


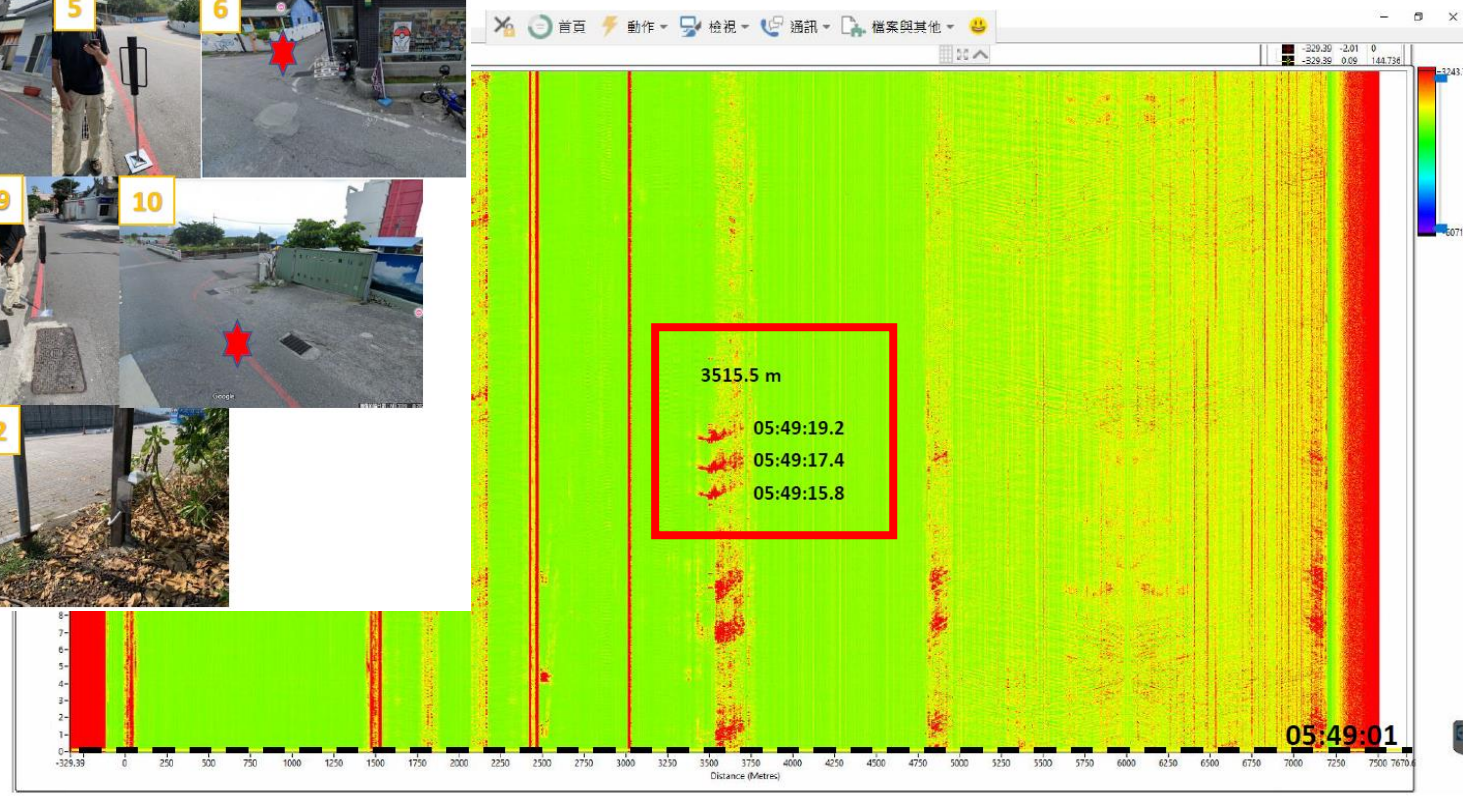




Tap test定位

Tap test on CHT segment (2022.09.19 UTC)

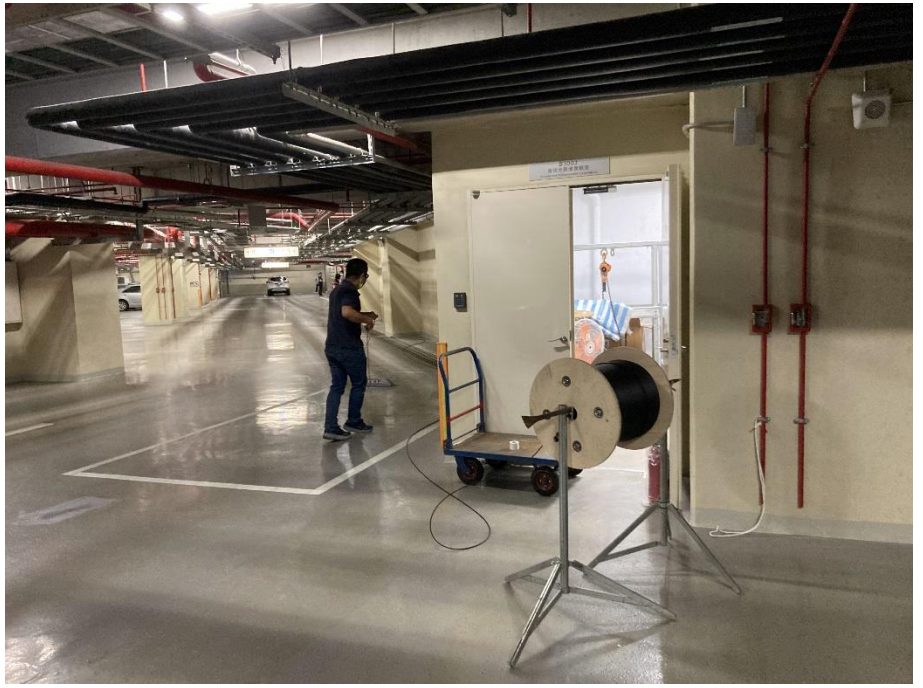


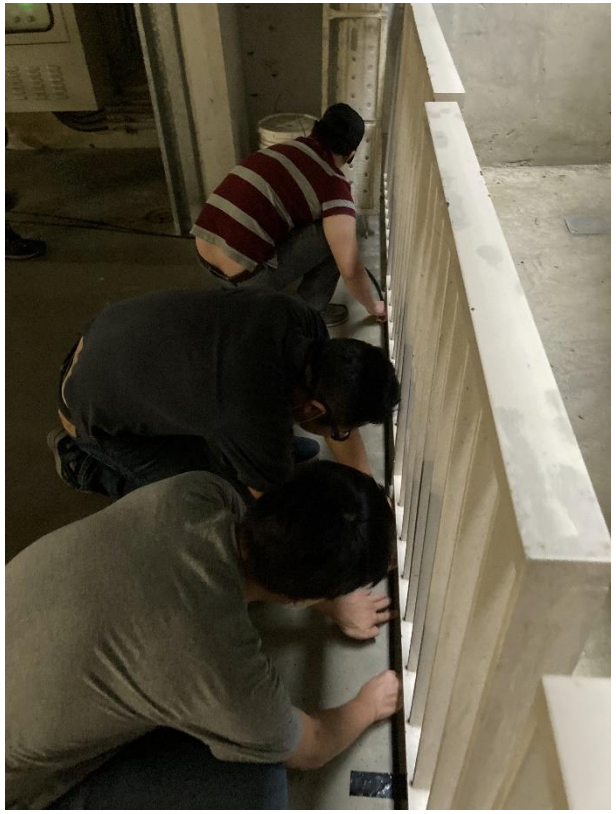


Courtesy of Chen-Ray

Fiber-ground coupling

Chin-Jen Lin, Hsin-Hua Huang , Chin-Shang Ku,
Ching-Chou Fu, Po-Li Su



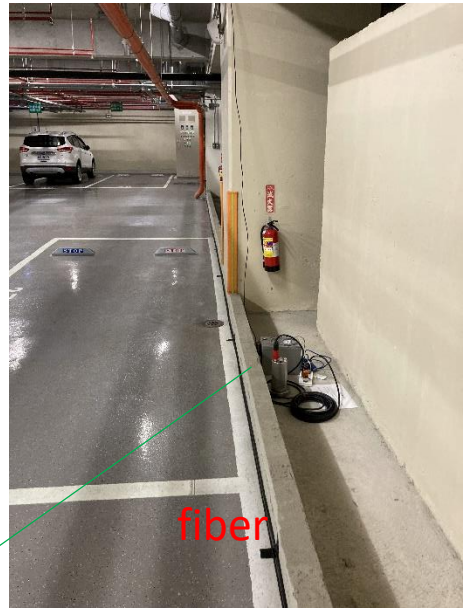


Fiber is taped on the ground

Three seismometers are separated

2021/11 ~

192.168.81.35
MC #581
TW.TR99



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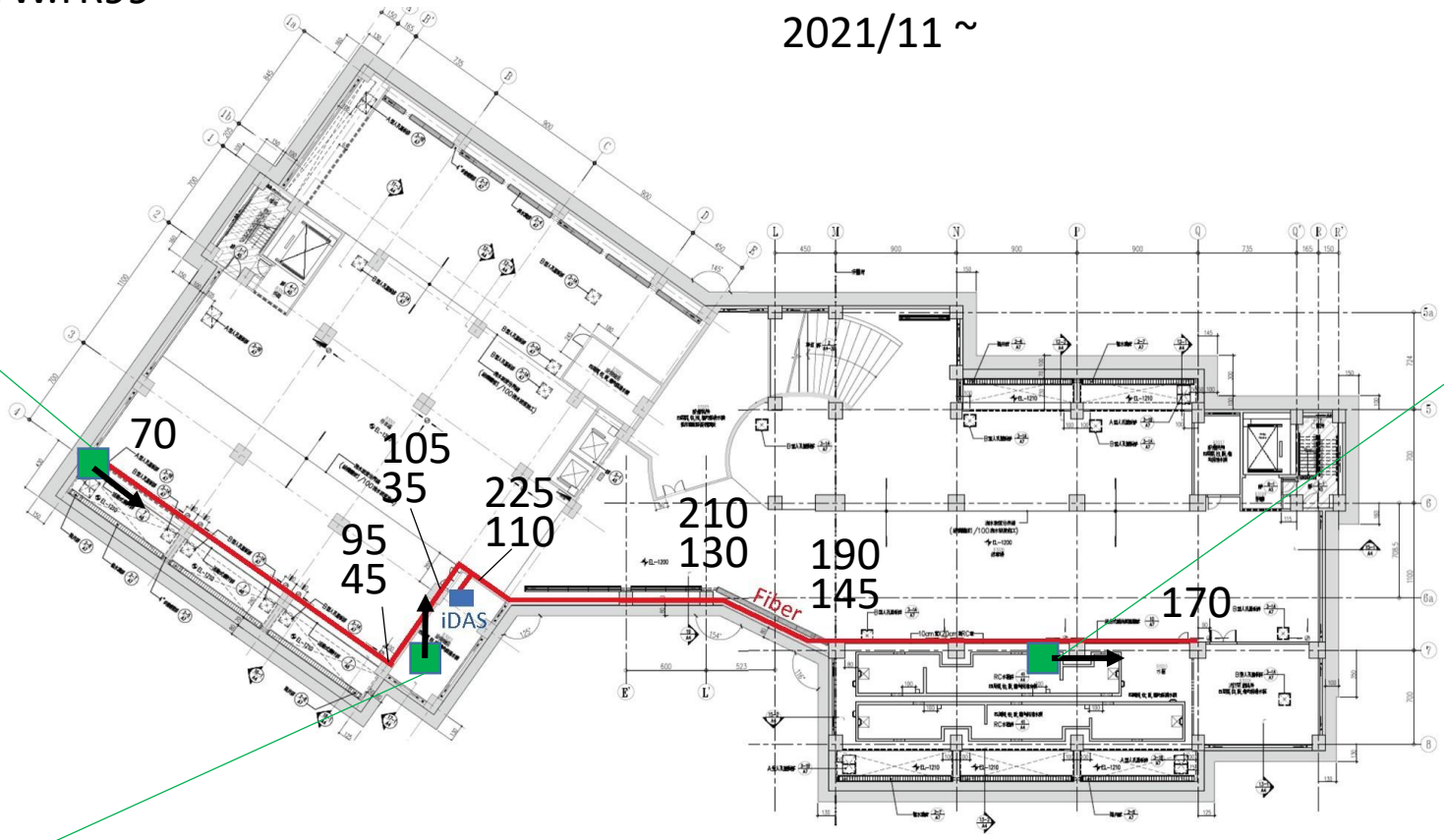
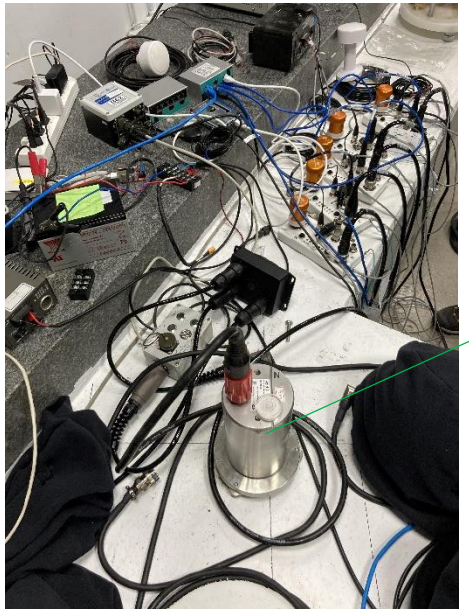
MC #582
TW.S0001

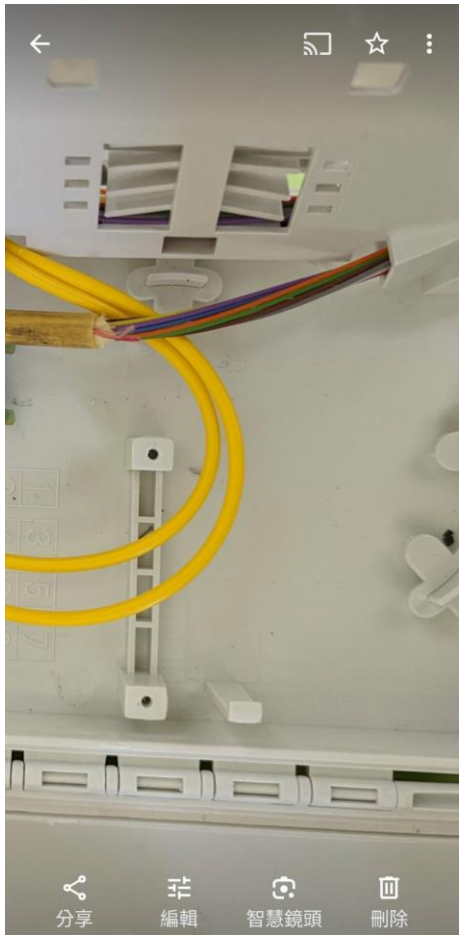




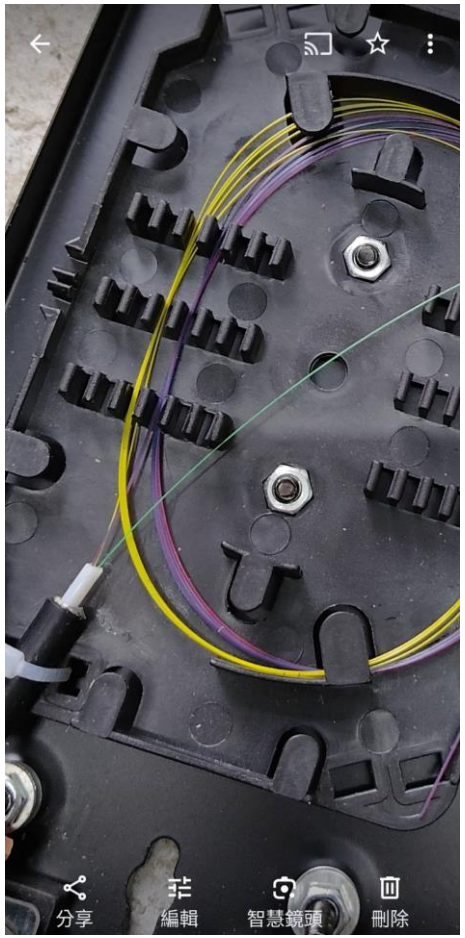
192.168.81.30
MC #745
FM.B330

* Three Nanometrics Meridian Compact postholes are used for strain derivation.

Cable difference

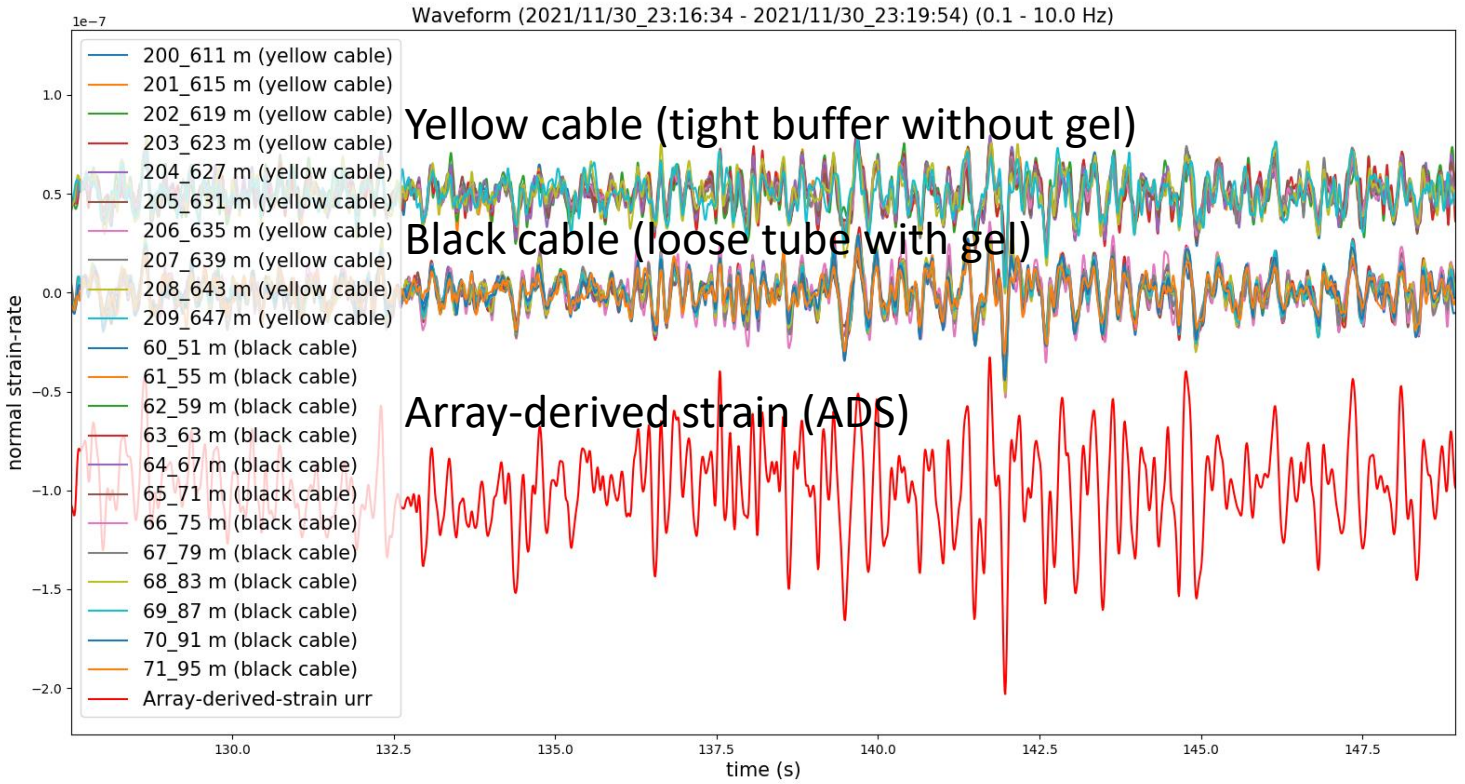


黃線和patch cable是tight buffer fiber

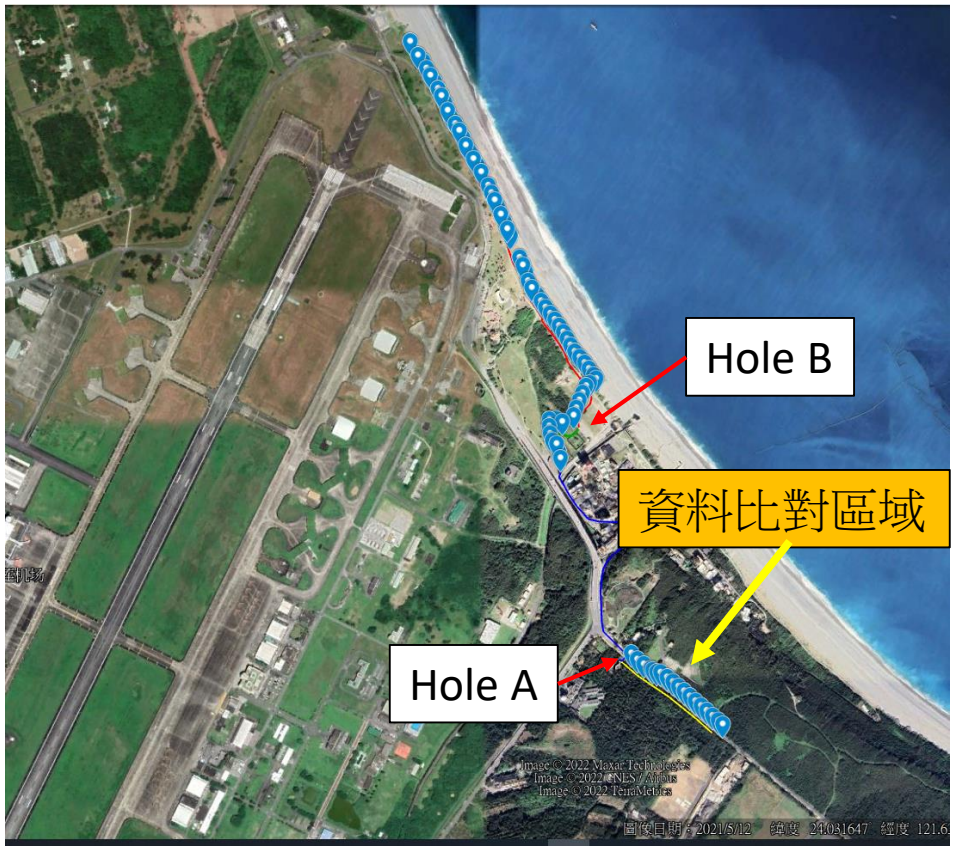


鋼纜跟黑纜是gel-filled loose tube fiber

It seems the amplitude level measuring from black cable is slightly larger than yellow cable, but the difference is not much. Both fiber cable waveform are less than array-derived strain, possibly due to the bad coupling between cable and ground surface.



MiDAS
Surface cable deployment

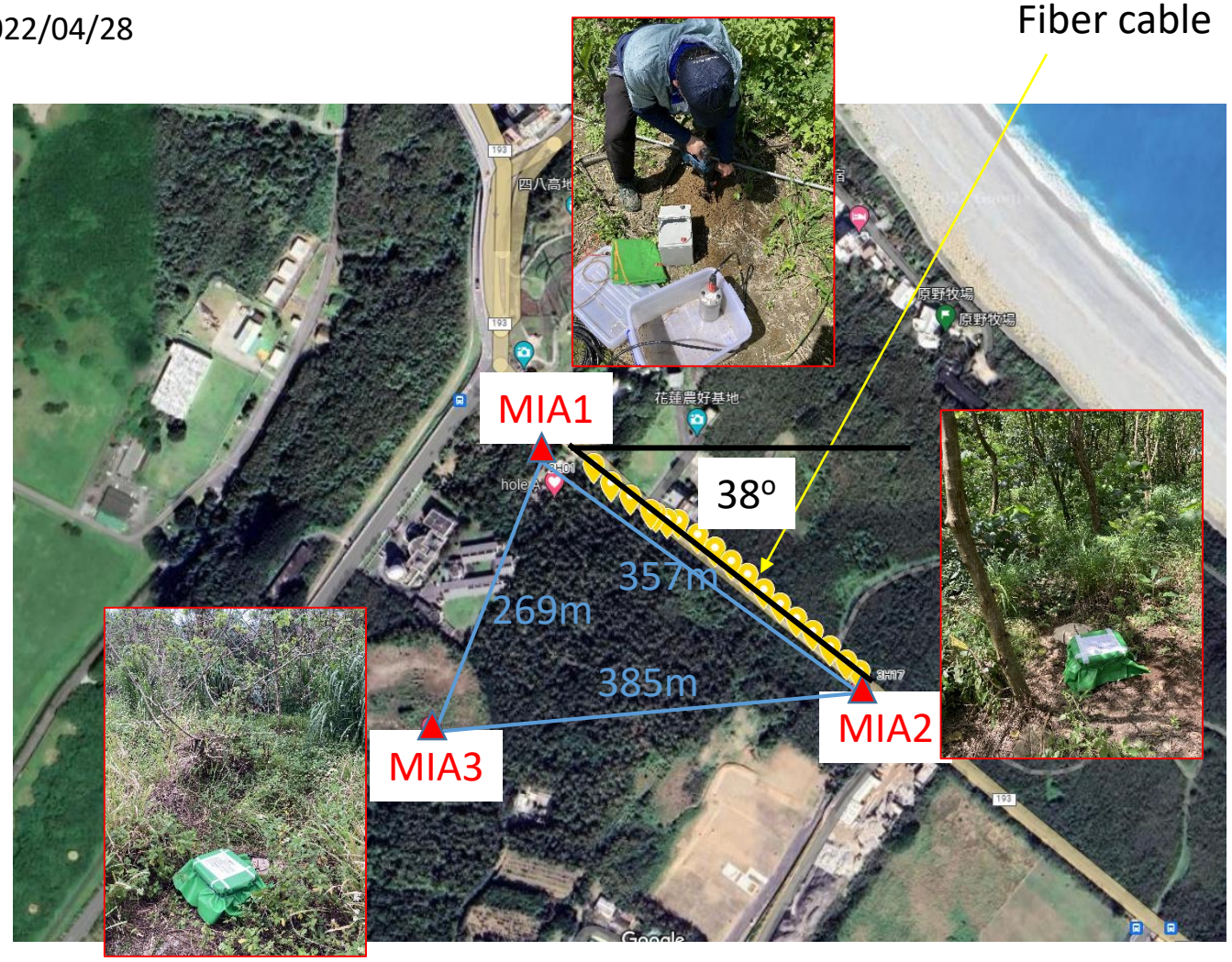


Surface cable bury at depth of 50 cm

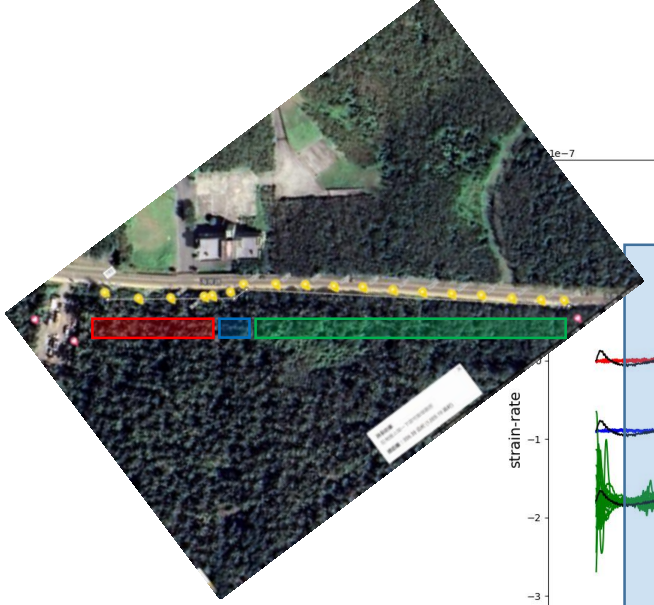
Seismic array temporary experiment

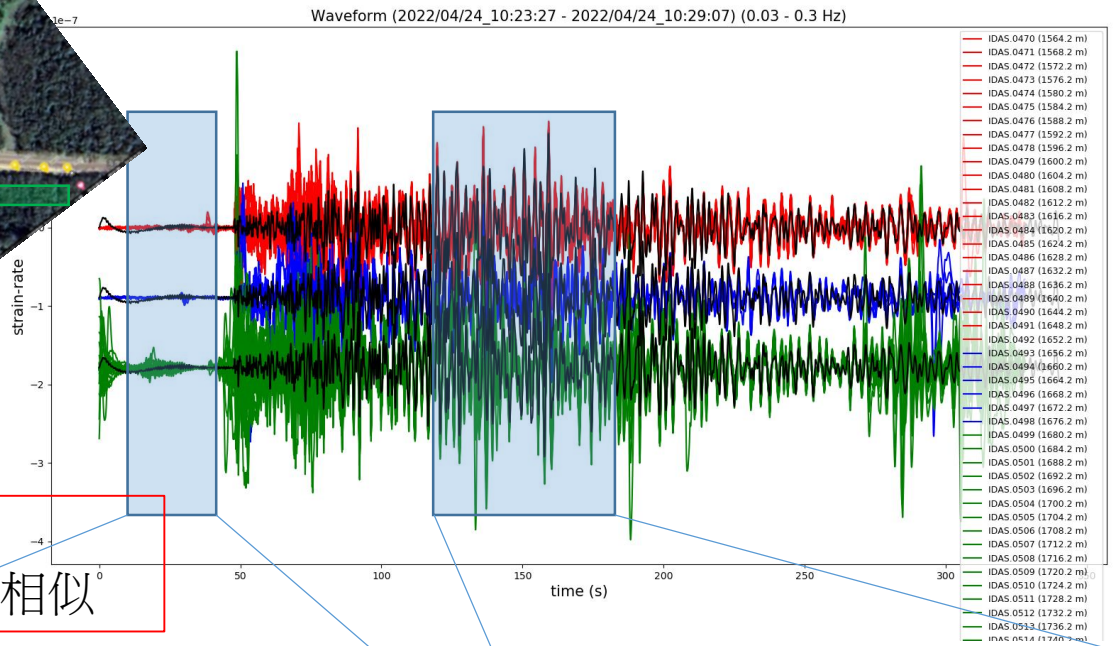
MIA1 Meridian Compact #581
MIA2 Meridian Compact #582
MIA3 Meridian Compact #409
Duration: 2022/03/25 ~ 2022/04/28

Meridian CompactPH

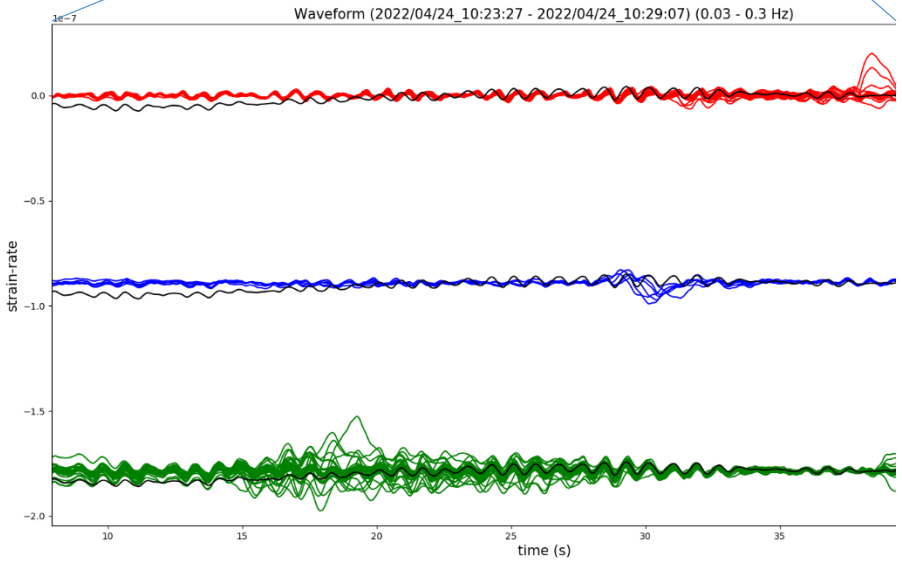


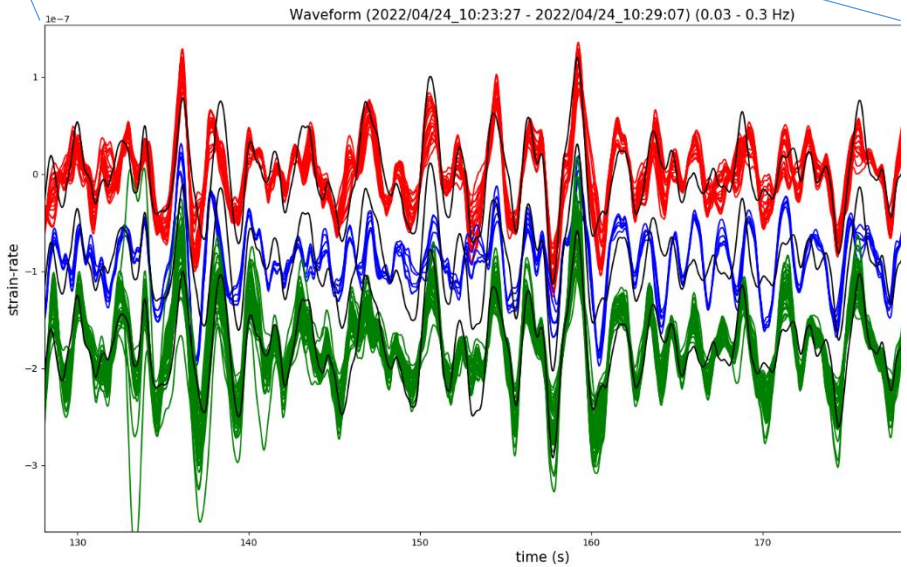
thank 紀宗志





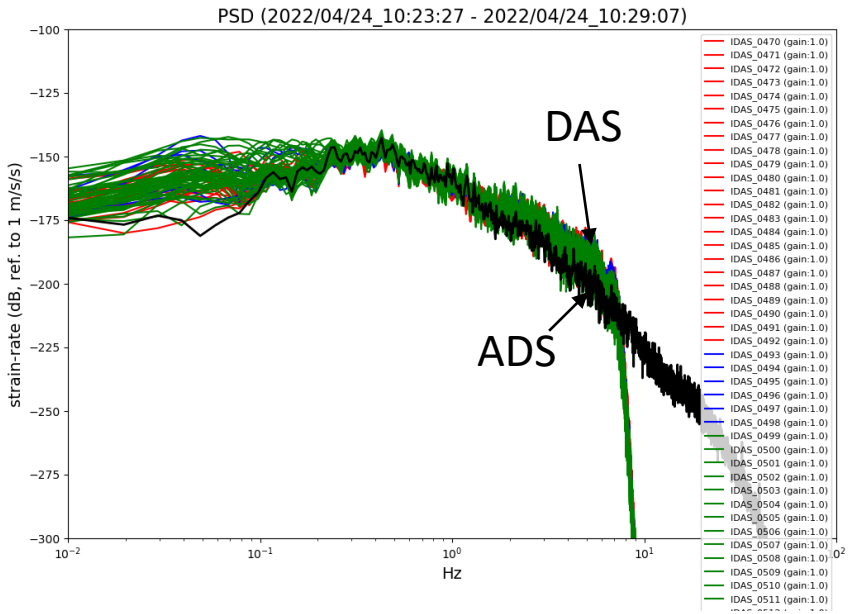
振幅比較
DAS 與 Array-derived strain (ADS)相似





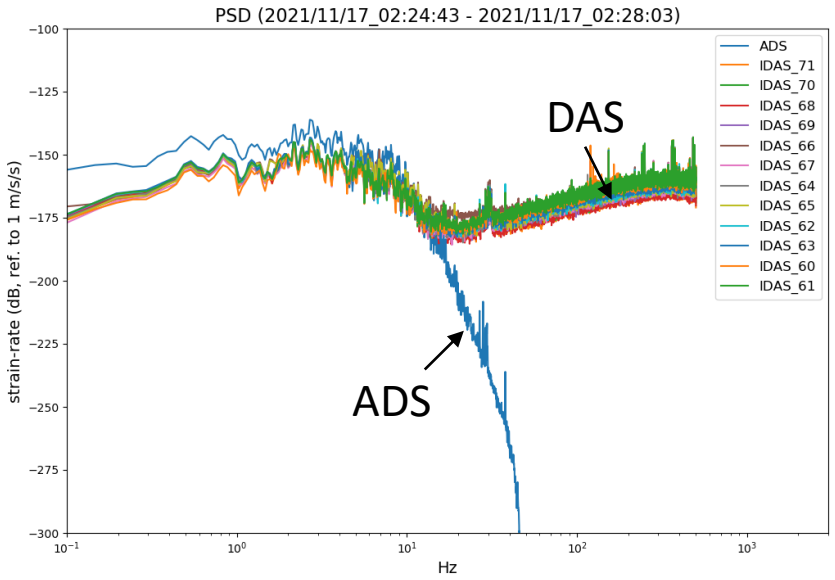
PSD

MiDAS



Good cable coupling
振幅比較: DAS 與 ADS相似

RCEC B3



Bad cable coupling
振幅比較: DAS < ADS

Conclusions

- DAS單價高，但是換成觀測點數量後則較地震儀划算
- 使用現有通訊光纖
- 高靈敏度：< 2 nm/s/sqrt Hz (gauge lenth 10m)
- 高時間取樣率：400 Hz – 100 KHz
- 長距離觀測：數十到百公里
- 即時觀測
- 光纖可深入惡劣環境
- 井下觀測光纖可以固定在鋼管外側
- 耐高溫 (-40C - 300 C)

謝謝聆聽!