

Signal to Noise Ratio Estimation of the ASCENDS CarbonHawk Experiment Simulator (ACES) for Atmospheric CO₂ Measurement

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Outlines

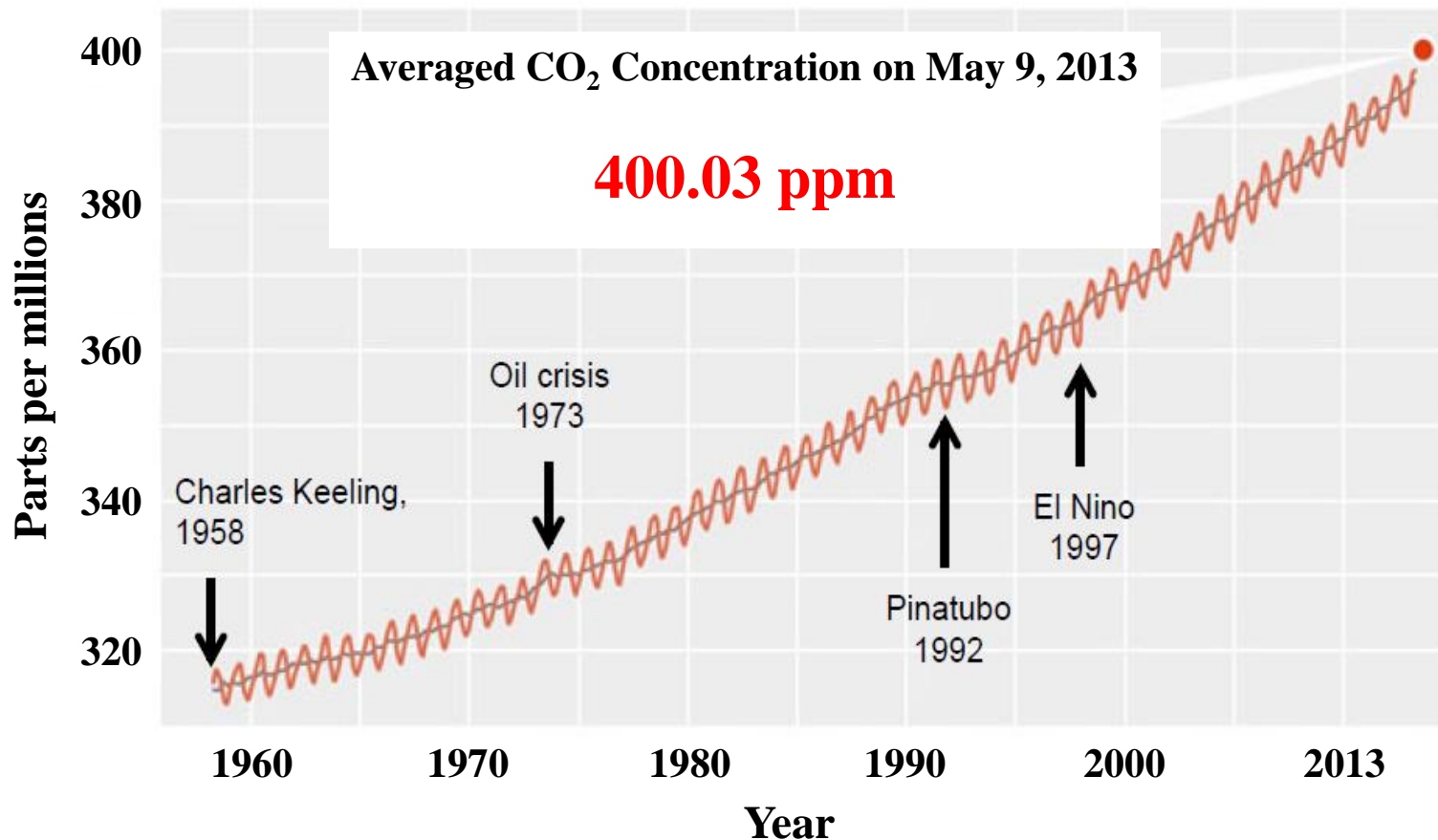


- **Introduction**
- **Maximum Likelihood Estimation (MLE) for Multiple Linear Swept-Frequency Sine-Wave Detection**
- **An Airborne Multiple Swept-Frequency (SF) Intensity-Modulated Continuous-Wave (IM-CW) ASCENDS CarbonHawk Experiment Simulator (ACES)**
 - Multiple swept-frequency IM-CW laser transmitter
 - Multiple swept-frequency IM-CW digital detection
 - MLE of multiple swept-frequency digitized IM-CW signals
- **Conclusions and Discussions**



Introduction-1

Carbon Dioxide (CO₂) Concentration in the Atmosphere (Increase)



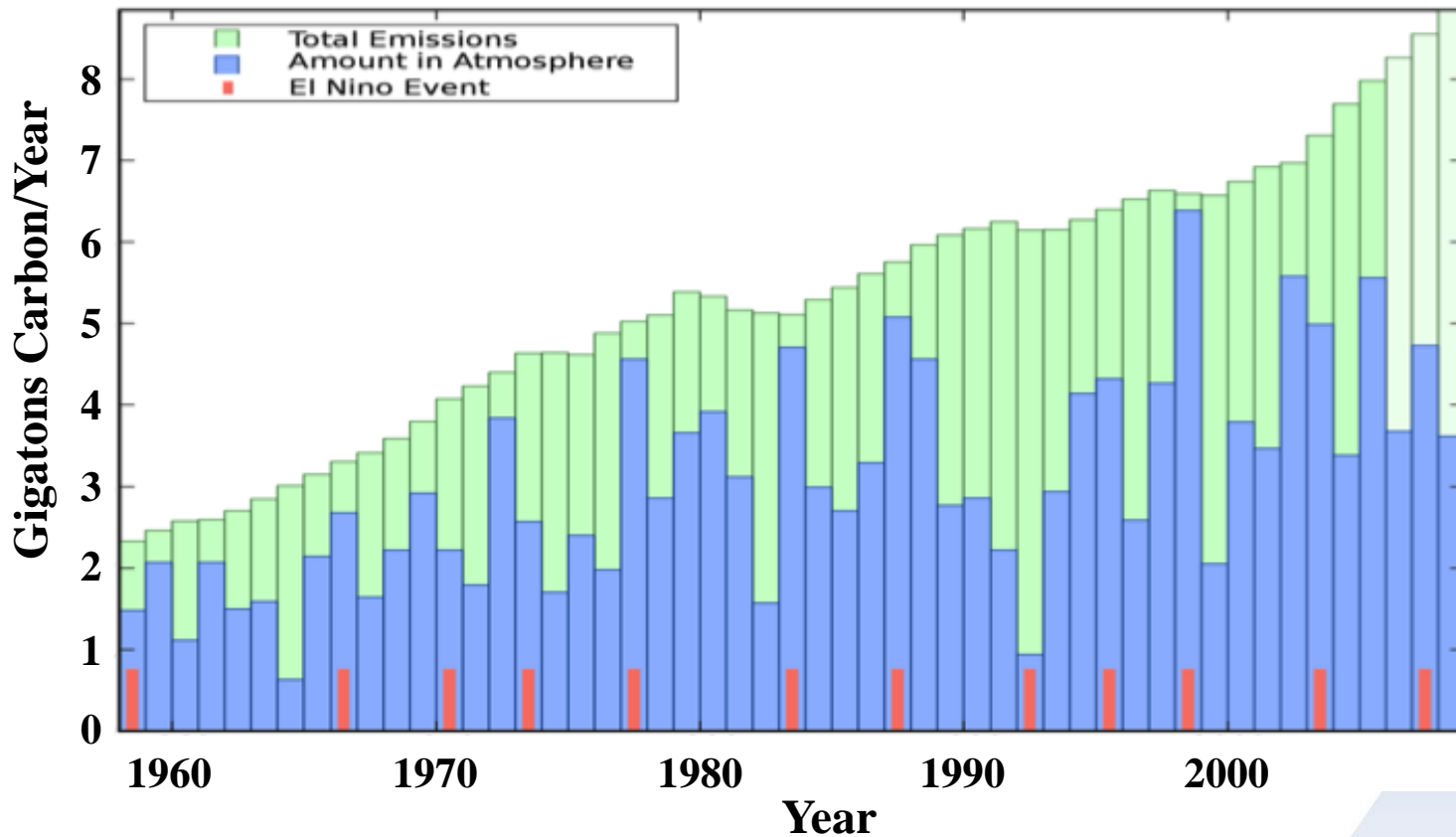
Based on NOAA/Scripps Institution of Oceanography



Introduction-2

CO₂ Sources and Sinks (Missing?)

Fossil Fuel Emissions of CO₂ and Atmospheric Buildup, 1958-2008



Based on LeQuere et al., 2009



Maximum Likelihood Estimation (MLE) -1



- MLE for analysis of the parameters of multiple-frequency digitized sine-wave signals based on a statistical model, all the digitized signals, $S(n)$, is sum of the expectation value of the signals and Gaussian-distributed random noise with the probability,

$$\Pr(S(n)) = \frac{1}{\sqrt{2\pi\sigma_n^2}} \exp\left(-\frac{(S(n) - E\langle S(n)\rangle)^2}{2\sigma_n^2}\right) \quad n = 0, 1, 2, \dots, N_s - 1$$

$E\langle S(n)\rangle$ is expected value of $S(n)$ and σ_n^2 is variance of the noise.

- MLE formula

$$\arg \max_{\text{over all variables}} (L) = \arg \max_{\text{over all variables}} \left(\prod_{n=0}^{N_s-1} \left(\frac{1}{\sqrt{2\pi\sigma_n^2}} \right) \exp\left(-\frac{(S(n) - E\langle S(n)\rangle)^2}{2\sigma_n^2}\right) \right)$$



Maximum Likelihood Estimation (MLE) -2

➤ Maximum Log-Likelihood Estimation Function l

$$\begin{aligned} \arg \max_{\text{over all variables}} (L) &= \exp \left(\arg \max_{\text{over all variables}} (\ln(L)) \right) \\ &= \exp \left(\arg \max_{\text{over all variables}} \left(-\frac{1}{2} \sum_{n=0}^{N_s-1} (2\pi\sigma_n^2) - \sum_{n=0}^{N_s-1} \left(\frac{(S(n) - E\langle S(n) \rangle)^2}{2\sigma_n^2} \right) \right) \right) \\ &\equiv \exp \left(\arg \max_{\text{over all variables}} (l') \right) \end{aligned}$$

$$l' = \left(-\frac{1}{2} \sum_{n=0}^{N_s-1} (2\pi\sigma_n^2) - \sum_{n=0}^{N_s-1} \left(\frac{(S(n) - E\langle S(n) \rangle)^2}{2\sigma_n^2} \right) \right)$$



Maximum Likelihood Estimation (MLE) -3

- Multiple Digitized Sine Wave Signals (numbers of k)

$$S(n) = \frac{1}{f_s} \left(S_c^0 + \sum_{i=1}^k S_i^0 \cos \left(2\pi \left(f_i^m + \frac{f_\Delta^m}{2} \frac{n}{f_s} \right) \frac{n}{f_s} + \varphi_i \right) + N_G \left(\frac{n}{f_s} \right) \right)$$
$$= \frac{1}{f_s} \sum_{i=1}^k \left(S_i^c \cos \left(2\pi \left(f_i^m + \frac{f_\Delta^m}{2} \frac{n}{f_s} \right) \frac{n}{f_s} \right) + S_i^s \sin \left(2\pi \left(f_i^m + \frac{f_\Delta^m}{2} \frac{n}{f_s} \right) \frac{n}{f_s} \right) + N_G \left(\frac{n}{f_s} \right) \right)$$

$$S_i^c = S_i^0 \cos(\varphi_i) \text{ and } S_i^s = -S_i^0 \sin(\varphi_i)$$

$$E\langle S(n) \rangle = S_c^0 + \sum_{i=1}^k \left(S_i^c \cos \left(2\pi \left(f_i^m + \frac{f_\Delta^m}{2} \frac{n}{f_s} \right) \frac{n}{f_s} \right) + S_i^s \sin \left(2\pi \left(f_i^m + \frac{f_\Delta^m}{2} \frac{n}{f_s} \right) \frac{n}{f_s} \right) \right)$$

f_i^m, φ_i : frequency and phase of the i^{th} swept-frequency signals

f_s : sampling frequency; S_c^0 : constant dc-term

$N_G \left(\frac{n}{f_s} \right)$: Gaussian-distributed noise term



Maximum Likelihood Estimation (MLE) -4

- Maximum Log-Likelihood Estimation Function l for Multiple Digitized Sine Wave Signals with constant Frequencies

$$\begin{aligned} & \arg \max_{\text{over all variables}} (l) \\ &= \arg \max_{S_1^c, \dots, S_k^c, S_c^0, S_1^s, \dots, S_k^s} \left(-\frac{1}{2} \sum_{n=0}^{N_s-1} (2\pi\sigma_n^2) - \sum_{n=0}^{N_s-1} \left(\frac{(S(n) - E\langle S(n) \rangle)^2}{2\sigma_n^2} \right) \right) \end{aligned}$$

This is the formula for the computer simulation of the MLE of the airborne multiple swept-frequency IM-CW ACES system

An Airborne Multiple SF IM-CW ACES

➤ Advances of airborne technologies in support of NASA ASCENDS mission

Airborne Platforms:



Hu-25



C-130



DC-8



GlobalHawk

- High and large altitude range: ~1.0 km - ~20 km

EDFA-based high-power Laser transmitter:

up to 3×10^4 W
(Avg.)



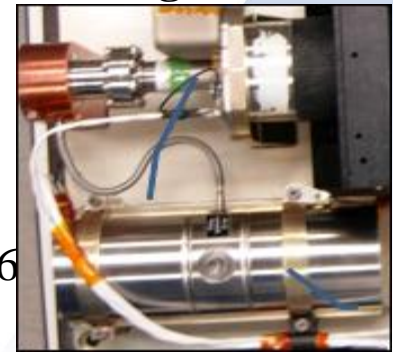
HgCdTe APD Array-based high-sensitive detector:

NEP: $2.4 \text{ fW/Hz}^{1/2}$

Temperature $\leq 77 \text{ K}$

Bandwidth:

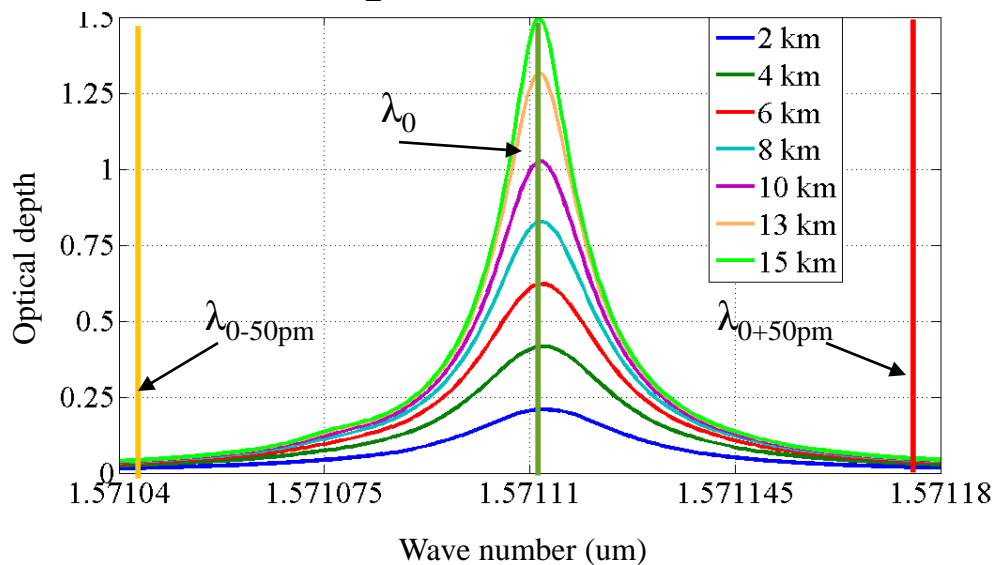
$\sim 4.9 \text{ MHz @ gain } 10^6$



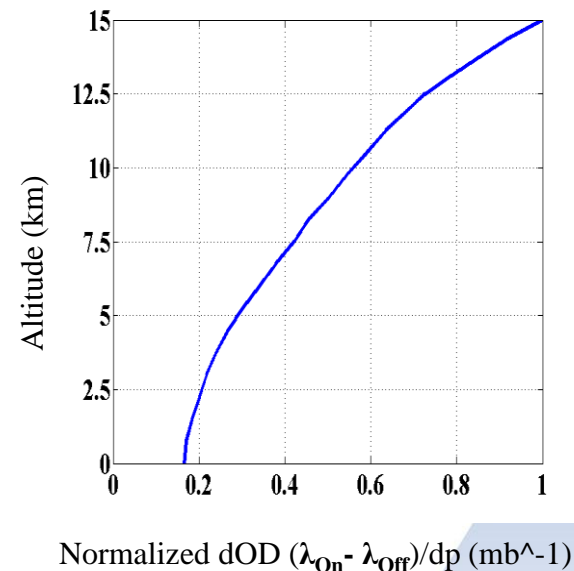
An Airborne Multiple SF IM-CW ACES

- Airborne multiple SF IM-CW ACES operated at Three Different Wavelengths around CO₂ Absorption Line of 1571nm

Two-Way Optical Depth at CO₂ Absorption Line



Line Weighting Functions at 1571nm



Calculated based on HITRAN 2008 Database, US standard atmosphere

$$\lambda_{\text{On}} = \lambda_0; \lambda_{\text{Off1}} = \lambda_0 - 50\text{pm}; \lambda_{\text{Off2}} = \lambda_0 + 50\text{pm}$$

$$\lambda_0 = 1571.11\text{nm} \text{ --- Center Wavelength}$$

An Airborne Multiple SF IM-CW ACES

➤ EDFA-Based high-power laser transmitter

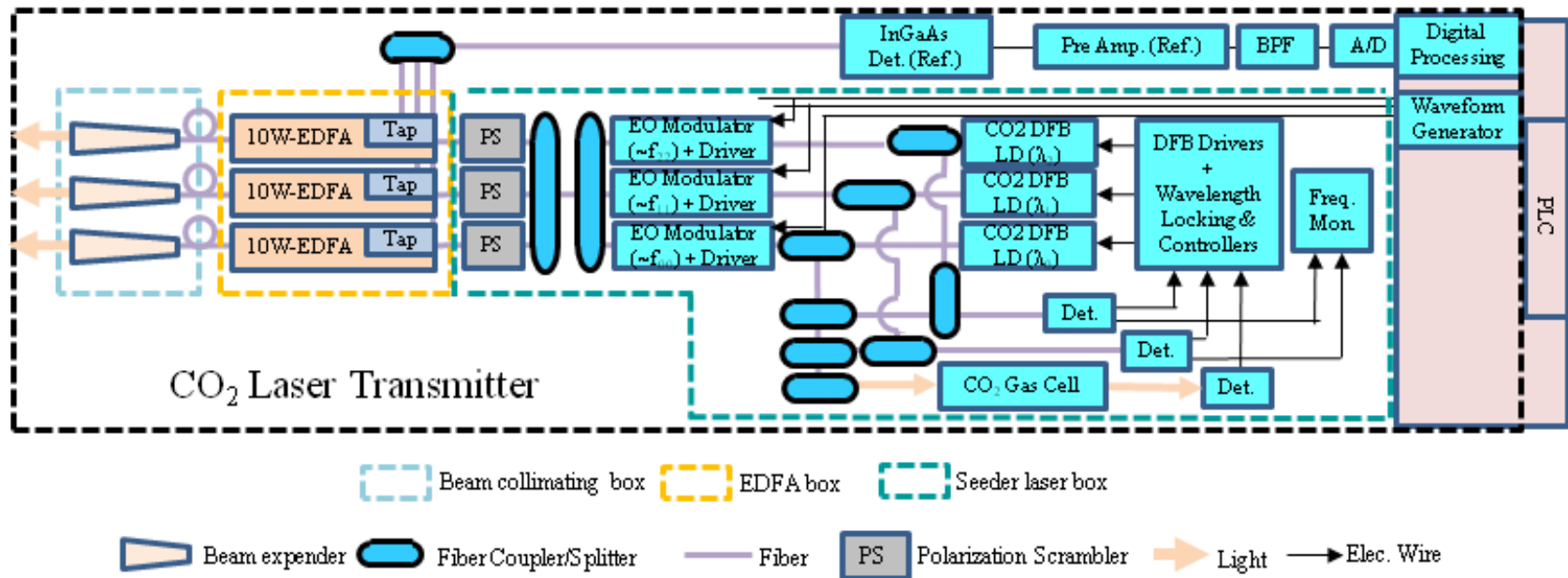


Diagram of EDFA-based Laser Transmitter of ACES

An Airborne Multiple SF IM-CW ACES

- Multiple SF IM-CW ACES optical and electrical digitized receiver

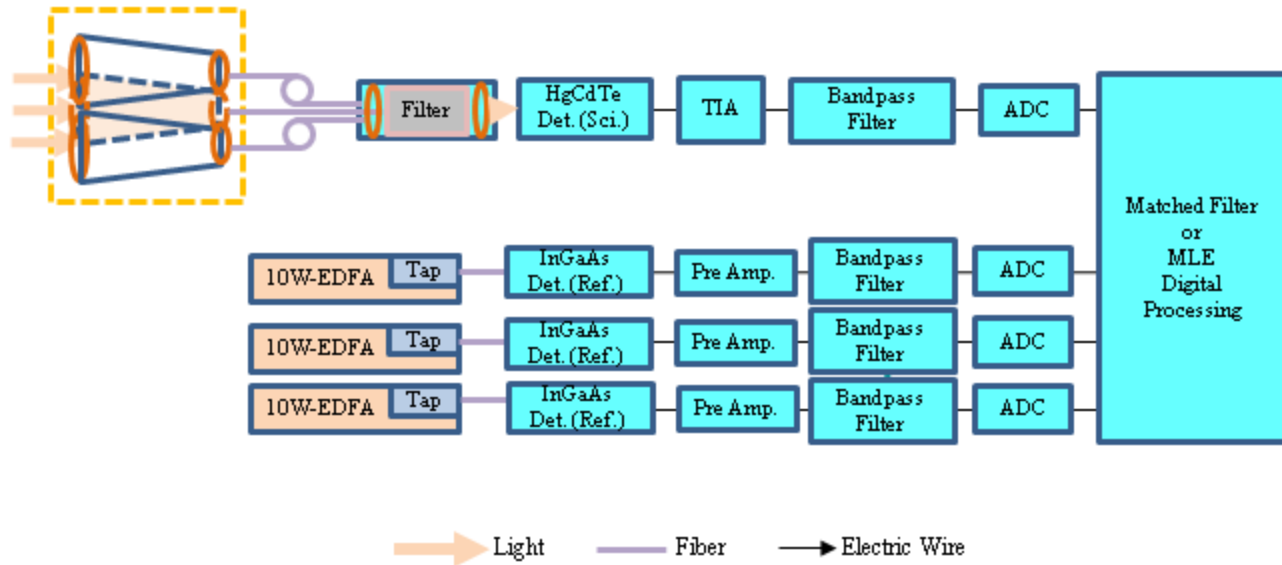


Diagram of ACES Optical and Electrical Digitized Receiver



An Airborne Multiple SF IM-CW ACES

➤ LIDAR Equation for the airborne multiple SF IM-CW ACES at three different aavelengths

- Total Received Signals under the Intrinsic Limit of Shot Noise

$$S_T^R(t) = \frac{D_T^2}{\pi R^2} \eta_q \eta_{opt} r_s \sum_{i=1}^3 S_{\lambda_i}^L(t) \frac{hc}{\lambda_i} \tau_{\lambda_i}^2 + S_{Solar}^B + S_{Dark}^B$$

$$= \frac{D_T^2}{\pi R^2} \eta_{opt} r_s \sum_{i=1}^3 S_{\lambda_i}^L(t) \eta_q \frac{hc}{\lambda_i} \tau_{\lambda_i}^2 + J \frac{\pi D_T^2}{4} \frac{\pi}{4} (FOV)^2 \eta_q \frac{hc}{\lambda_0} \eta_{opt} \tau_{eff}^a (\Delta\lambda) + S_{Dark}^B$$

$$S_{\lambda_i}^L(t) = S_i^0 (1 + m_i) \cos \left(2\pi \left(f_i^m + \frac{f_{\Delta}^m}{2} t \right) t + \varphi_i \right) \text{ and } OD_{\lambda_i} = -\ln(\tau_{\lambda_i}^2)$$

$S_{\lambda_i}^L(t)$ S_i^0 m_i : Laser signals, Signal amplitude, Modulation index at λ_i ;
 $\tau_{\lambda_i}^2$ and OD_{λ_i} : Two-way atmospheric transmittance and optical depth at λ_i ;
 η_q and η_{opt} : Detector quantum efficiency and system optical efficiency;
 D_T , r_s , τ_{eff}^a , and $(\Delta\lambda)$: Dia. Of Telescope, Surface reflectance, Effective atmospheric transmittance and bandwidth near CO₂ absorption line at 1571 nm
 R , J , θ , $(\Delta\lambda)$: Transmitter-Target range, Solar background induced photon radiance and scattering, and FOV of telescope



An Airborne Multiple SF IM-CW ACES

- **Maximum Likelihood Estimation of the Digitized Multiple-Frequency IM-CW Signals at Three Different Wavelengths**
 - Gaussian noise assumption: Detected laser signal photons, solar background photons, and detector dark current – contributed numbers of electric charges (electron) during one sampling period are more than 15-20

Total detected signal in a simple format:

$$S(t) = S_c^0 + \sum_{i=1}^3 S_i^0 \cos(2\pi f_i^m t + \varphi_i) + N_G(t)$$
$$= S_c^0 + \sum_{i=1}^3 \left(S_i^c \cos(2\pi f_i^m t) + S_i^c \sin(2\pi f_i^m t) \right) + N_G(t)$$



An Airborne Multiple SF IM-CW ACES

➤ Maximum Likelihood Estimation of the digitized multiple SF IM-CW Signals at three different wavelengths

- Gaussian noise assumption: Detected laser signal photons, solar background photons, and detector dark current – contributed numbers of electric charges (electron) during one sampling period are more than 15-20
- Gaussian noise with constant variance: Simpler case for solar background photon and detector dark current contributed shot noise is much larger than signal shot noise $\sigma_n^2 = \sigma^2$ proportional to total detected solar background photons at low detector dark current. Simple MLE formula

$$\arg \max_{S_1^c, \dots, S_k^c, S_c^0, S_1^s, \dots, S_k^s} (l) \equiv \arg \max_{S_1^c, \dots, S_k^c, S_c^0, S_1^s, \dots, S_k^s} \left(- \sum_{n=0}^{N_s-1} \left(\frac{(S(n) - E\langle S(n) \rangle)^2}{2\sigma^2} \right) \right)$$

An Airborne Multiple SF IM-CW ACES

- **Maximum Likelihood Estimation of the digitized multiple SF IM-CW Signals at three different wavelengths**

$$\begin{bmatrix} \mathfrak{R}_{11} & \mathfrak{R}_{12} & \mathfrak{R}_{13} & \mathfrak{R}_{14} & \mathfrak{R}_{15} & \mathfrak{R}_{16} & \mathfrak{R}_{17} \\ \mathfrak{R}_{21} & \mathfrak{R}_{22} & \mathfrak{R}_{23} & \mathfrak{R}_{24} & \mathfrak{R}_{25} & \mathfrak{R}_{26} & \mathfrak{R}_{27} \\ \mathfrak{R}_{31} & \mathfrak{R}_{32} & \mathfrak{R}_{33} & \mathfrak{R}_{34} & \mathfrak{R}_{35} & \mathfrak{R}_{36} & \mathfrak{R}_{37} \\ \mathfrak{R}_{41} & \mathfrak{R}_{42} & \mathfrak{R}_{43} & \mathfrak{R}_{44} & \mathfrak{R}_{45} & \mathfrak{R}_{46} & \mathfrak{R}_{47} \\ \mathfrak{R}_{51} & \mathfrak{R}_{52} & \mathfrak{R}_{53} & \mathfrak{R}_{54} & \mathfrak{R}_{55} & \mathfrak{R}_{56} & \mathfrak{R}_{57} \\ \mathfrak{R}_{61} & \mathfrak{R}_{62} & \mathfrak{R}_{63} & \mathfrak{R}_{64} & \mathfrak{R}_{65} & \mathfrak{R}_{66} & \mathfrak{R}_{67} \\ \mathfrak{R}_{71} & \mathfrak{R}_{72} & \mathfrak{R}_{73} & \mathfrak{R}_{74} & \mathfrak{R}_{75} & \mathfrak{R}_{76} & \mathfrak{R}_{77} \end{bmatrix} \begin{bmatrix} S_1^c \\ S_2^c \\ S_3^c \\ S_c^0 \\ S_1^s \\ S_2^s \\ S_3^s \end{bmatrix} = \begin{bmatrix} \sum_{n=0}^{N_s-1} S_n \cos\left(2\pi \frac{f_1^m}{f_s} n\right) \\ \sum_{n=0}^{N_s-1} S_n \cos\left(2\pi \frac{f_2^m}{f_s} n\right) \\ \sum_{n=0}^{N_s-1} S_n \cos\left(2\pi \frac{f_3^m}{f_s} n\right) \\ \sum_{n=0}^{N_s-1} S_n \\ \sum_{n=0}^{N_s-1} S_n \sin\left(2\pi \frac{f_1^m}{f_s} n\right) \\ \sum_{n=0}^{N_s-1} S_n \sin\left(2\pi \frac{f_2^m}{f_s} n\right) \\ \sum_{n=0}^{N_s-1} S_n \sin\left(2\pi \frac{f_3^m}{f_s} n\right) \end{bmatrix}$$

An Airborne Multiple SF IM-CW ACES

$$\Re_{51} = \frac{1}{2} \sum_{n=0}^{N_s-1} \left(\sin \left(2\pi \left((f_1^m + f_3^m) \frac{n}{f_s} + f_{\Delta}^m \frac{n^2}{f_s^2} \right) \right) - \sin \left(2\pi \left((f_1^m - f_3^m) \frac{n}{f_s} \right) \right) \right)$$

$$\Re_{55} = \frac{1}{2} \sum_{n=0}^{N_s-1} \left(1 - \cos \left(4\pi \left(f_3^m \frac{n}{f_s} + \frac{1}{2} f_{\Delta}^m \frac{n^2}{f_s^2} \right) \right) \right)$$

$$\Re_{52} = \frac{1}{2} \sum_{n=0}^{N_s-1} \left(\sin \left(2\pi \left((f_2^m + f_3^m) \frac{n}{f_s} + f_{\Delta}^m \frac{n^2}{f_s^2} \right) \right) - \sin \left(2\pi \left((f_2^m - f_3^m) \frac{n}{f_s} \right) \right) \right)$$

$$\Re_{56} = \frac{1}{2} \sum_{n=0}^{N_s-1} \left(\cos \left(2\pi \left((f_2^m + f_3^m) \frac{n}{f_s} + f_{\Delta}^m \frac{n^2}{f_s^2} \right) \right) - \cos \left(2\pi \left((f_2^m - f_3^m) \frac{n}{f_s} \right) \right) \right)$$

$$\Re_{53} = \frac{1}{2} \sum_{n=0}^{N_s-1} \left(\sin \left(4\pi \left(f_3^m \frac{n}{f_s} + \frac{1}{2} f_{\Delta}^m \frac{n^2}{f_s^2} \right) \right) \right)$$

$$\Re_{57} = \frac{1}{2} \sum_{n=0}^{N_s-1} \left(\cos \left(2\pi \left((f_1^m + f_3^m) \frac{n}{f_s} + f_{\Delta}^m \frac{n^2}{f_s^2} \right) \right) - \cos \left(2\pi \left((f_1^m - f_3^m) \frac{n}{f_s} \right) \right) \right)$$

$$\Re_{54} = \sum_{n=0}^{N_s-1} \sin \left(2\pi \left(f_3^m \frac{n}{f_s} + \frac{1}{2} f_{\Delta}^m \frac{n^2}{f_s^2} \right) \right)$$

$$\Re_{61} = \frac{1}{2} \sum_{n=0}^{N_s-1} \left(\sin \left(2\pi \left((f_1^m + f_2^m) \frac{n}{f_s} + f_{\Delta}^m \frac{n^2}{f_s^2} \right) \right) - \sin \left(2\pi \left((f_1^m - f_2^m) \frac{n}{f_s} \right) \right) \right)$$

$$\Re_{65} = \frac{1}{2} \sum_{n=0}^{N_s-1} \left(\cos \left(2\pi \left((f_1^m + f_2^m) \frac{n}{f_s} + f_{\Delta}^m \frac{n^2}{f_s^2} \right) \right) - \cos \left(2\pi \left((f_1^m - f_2^m) \frac{n}{f_s} \right) \right) \right)$$

$$\Re_{62} = \frac{1}{2} \sum_{n=0}^{N_s-1} \left(\sin \left(4\pi \left(f_2^m \frac{n}{f_s} + \frac{1}{2} f_{\Delta}^m \frac{n^2}{f_s^2} \right) \right) \right)$$

$$\Re_{66} = \frac{1}{2} \sum_{n=0}^{N_s-1} \left(1 - \cos \left(4\pi \left(f_2^m \frac{n}{f_s} + \frac{1}{2} f_{\Delta}^m \frac{n^2}{f_s^2} \right) \right) \right)$$

$$\Re_{63} = \frac{1}{2} \sum_{n=0}^{N_s-1} \left(\sin \left(2\pi \left((f_2^m + f_3^m) \frac{n}{f_s} + f_{\Delta}^m \frac{n^2}{f_s^2} \right) \right) + \sin \left(2\pi \left((f_2^m - f_3^m) \frac{n}{f_s} \right) \right) \right)$$

$$\Re_{67} = \frac{1}{2} \sum_{n=0}^{N_s-1} \left(\cos \left(2\pi \left((f_2^m + f_3^m) \frac{n}{f_s} + f_{\Delta}^m \frac{n^2}{f_s^2} \right) \right) - \cos \left(2\pi \left((f_2^m - f_3^m) \frac{n}{f_s} \right) \right) \right)$$

$$\Re_{64} = \sum_{n=0}^{N_s-1} \sin \left(2\pi \left(f_2^m \frac{n}{f_s} + \frac{1}{2} f_{\Delta}^m \frac{n^2}{f_s^2} \right) \right)$$

$$\Re_{71} = \frac{1}{2} \sum_{n=0}^{N_s-1} \left(\sin \left(4\pi \left(f_1^m \frac{n}{f_s} + \frac{1}{2} f_{\Delta}^m \frac{n^2}{f_s^2} \right) \right) \right)$$

$$\Re_{75} = \frac{1}{2} \sum_{n=0}^{N_s-1} \left(\cos \left(2\pi \left((f_1^m + f_3^m) \frac{n}{f_s} + f_{\Delta}^m \frac{n^2}{f_s^2} \right) \right) - \cos \left(2\pi \left((f_1^m - f_3^m) \frac{n}{f_s} \right) \right) \right)$$

$$\Re_{72} = \frac{1}{2} \sum_{n=0}^{N_s-1} \left(\sin \left(2\pi \left((f_1^m + f_2^m) \frac{n}{f_s} + f_{\Delta}^m \frac{n^2}{f_s^2} \right) \right) + \sin \left(2\pi \left((f_1^m - f_2^m) \frac{n}{f_s} \right) \right) \right)$$

$$\Re_{76} = \frac{1}{2} \sum_{n=0}^{N_s-1} \left(\cos \left(2\pi \left((f_1^m + f_2^m) \frac{n}{f_s} + f_{\Delta}^m \frac{n^2}{f_s^2} \right) \right) - \cos \left(2\pi \left((f_1^m - f_2^m) \frac{n}{f_s} \right) \right) \right)$$

$$\Re_{73} = \frac{1}{2} \sum_{n=0}^{N_s-1} \left(\sin \left(2\pi \left((f_1^m + f_3^m) \frac{n}{f_s} + f_{\Delta}^m \frac{n^2}{f_s^2} \right) \right) + \sin \left(2\pi \left((f_1^m - f_3^m) \frac{n}{f_s} \right) \right) \right)$$

$$\Re_{77} = \frac{1}{2} \sum_{n=0}^{N_s-1} \left(1 - \cos \left(4\pi \left(f_1^m \frac{n}{f_s} + \frac{1}{2} f_{\Delta}^m \frac{n^2}{f_s^2} \right) \right) \right)$$

$$\Re_{74} = \sum_{n=0}^{N_s-1} \sin \left(2\pi \left(f_1^m \frac{n}{f_s} + \frac{1}{2} f_{\Delta}^m \frac{n^2}{f_s^2} \right) \right)$$



An Airborne Multiple SF IM-CW ACES

➤ Simplified linear equations

Coefficient matrix R: off-diagonal components can be zero under following cases,

- * Sampling frequency is much larger than modulation frequencies**
- ** Specified sampling frequency, all modulation frequencies, and integration time periods.**

Our simulation condition:

SF signals at three different wavelengths:

Sampling frequency: 2 MHz

Swept frequencies: 100.4 kHz-600.4 kHz; 105.2 kHz-605.2 kHz;
and 110.8 kHz-610.8 kHz

Frequency increase rate (chirp rate): 2500 MHz

Orthogonal sweeping time: 5 ms (25 swept)

Integration time periods: 5ms, 25ms, 50ms, 100ms

➤ The Fractional/Relative Random Error of the CO₂ measurement

$$\left(\frac{\delta(\overline{N_{CO_2}})}{\overline{N_{CO_2}}} \right)_{On-Offi} = \sqrt{\left(\frac{\sigma(\delta(dOD_{On-Offi}))}{dOD_{On-Offi}} \right)^2 + \left(\frac{\sigma(\delta R)}{R} \right)^2}; \quad \frac{\sigma(\delta(dOD_{On-Offi}))}{dOD_{On-Offi}} = \frac{1}{dOD_{On-Offi}} \left(\frac{1}{SNR_{On}^R} + \frac{1}{SNR_{Offi}^R} \right)$$

$$\sigma(\delta R) \approx \frac{c}{2\sqrt{2}\pi} \sqrt{\left(\frac{1}{f_1^m m_1 SNR_{On}^R} \right)^2 + \left(\frac{1}{f_{i+1}^m m_{i+1} SNR_{Offi}^R} \right)^2} \approx \frac{c}{4\pi} \left(\frac{1}{f_1^m m_1 SNR_{On}^R} + \frac{1}{f_{i+1}^m m_{i+1} SNR_{Offi}^R} \right)$$

$$\overline{f_1^m}, \overline{f_{i+1}^m} \approx 350 \text{kHz}; \quad i = 1, 2; \quad c = 3 * 10^8 \text{ m/s}$$

$$\left(\frac{\delta(\overline{N_{CO_2}})}{\overline{N_{CO_2}}} \right)_{On-Offi}$$

Fractional/relative errors of the CO₂ column density measurement

$$dOD_{On-Offi}$$

Differential optical depth of the transmitted signals in the atmosphere between on-line and offline (1 or 2) wavelengths

$$SNR_{On}^L \text{ and } SNR_{Offi}^L$$

Signal to Noise Ratio (SNR) at on-line and off-line (1 or 2) wavelengths on the transmitter detector for laser power monitor

$$SNR_{On}^R \text{ and } SNR_{Offi}^R$$

Signal to Noise Ratio (SNR) at on-line and off-line (1 or 2) wavelengths on the detector of the receiver for signal measurement

$$dOD_{On-Offi} = -\ln\left(\frac{\tau_{On}^2}{\tau_{Offi}^2} \right) \tau_{On}^2 \text{ and } \tau_{Offi}^2 \text{ are two-way transmittance at on-line and off-line (1 or 2) wavelengths}$$



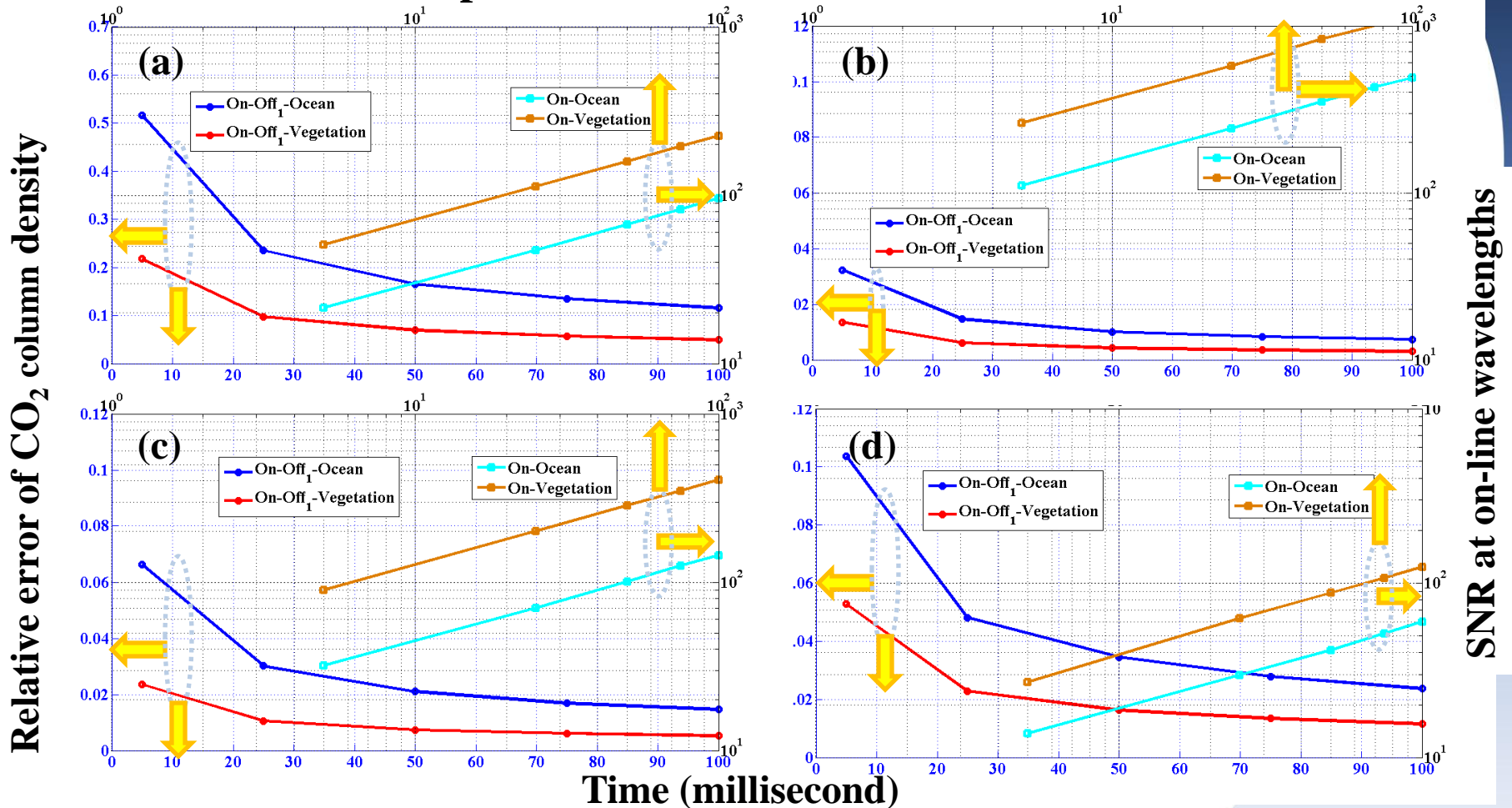
An Airborne Multiple SF IM-CW ACES

System Parameters for Computer Simulation of MLE

Altitude:	2-15 km
Receiving telescope:	
Effective Diameter:	$3 \cdot (0.17 / \sqrt{3})$ m
(3 7" Ritchey-Chretien telescopes with center blocks in ~2" dia.)	
FOV (full angle):	495 μ rad
Over all optical transmittance	8.5 %
Optical filter bandwidth:	2.7 nm
Laser transmitter:	
Beam divergence:	300 μ rad
Modulation index:	0.9
Photodetector: (HgTeCd APD 8*8 array)	
Noise Equivalent Power (NEP):	$2.4 \text{ fW/Hz}^{1/2} @ \sim 77\text{K}$
Quantum efficiency:	0.8
Ground radiance near 1571 nm:	
(W/m ² /sr/ μ m)	
ocean/vegetable	1.7/5.0
Surface reflectance:	
ocean/vegetable	0.08/0.31
Atmospheric transmittance for radiance	95%

An Airborne Multiple SF IM-CW ACES

Computer Simulated MLE Results



(a): Total Power: 5W@2km (b): Total Power: 10W@6km
 (c): Total Power: 10W@10km (d): Total Power: 30W@15km

Total Power distributed to different wavelength based on the atmospheric transmissions



Conclusions and Discussions



- **MLE of multiple digitized swept-frequency (SF) Intensity wave signals with Gaussian-distributed noise**
- **SNRs and relative errors of the CO₂ column density measurement from airborne at different altitudes have been simulated for the airborne SF IM-CW ACES**
- **SNRs increases as integration time increases up to 0.1s (linearly in log scales)**