An Off-Axis Laser-Radiation Detection Based on Intensity Interferometry

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we discuss an approach

- to detecting (off-axis) radiation of laser beam propagating in a scattering medium (in particular in the atmosphere)
- in the presence of strong incoherent background (solar) radiation

the approach is based on generalization of conventional intensity interferometry to scenarios involving coexisting sources of long (laser radiation) and much shorter (background) coherence times

the approach relies on a high degree of temporal coherence as the distinguishing property of the laser beam

■ motivation

► high-energy laser (HEL) systems are becoming a reality and developing countermeasures will also become a necessity

here we concentrate on detection of such laser beams and localization of their sources

it is desirable to be able to identify HEL beams from a “safe location”, by observing off-axis radiation due to the beam being scattered on the atmosphere particles

off-axis radiation may be relatively weak and may have to compete with the strong incoherent (e.g., solar) background

► in the current (and early) findings we concentrate on a problem of stationary radiation associated with HEL beams

► the approach can be generalized to pulsed radiation and applied in laser warning systems for detection of other radiation sources (e.g., laser-based range-finders, target designators) in the presence of strong incoherent background radiation
steps

- describe the theoretical basis of the proposed approach
  
  - an extension of the conventional *intensity interferometry (II)* method to a problem involving *different, coexisting* types of radiation,

  \[ \text{coherent: laser} \quad \text{incoherent: background} \]

- assess feasibility of the method (essentially, how high background radiation can be tolerated)

- sketch a possible design of a simple detector system
The underlying idea of the approach

- distinctive properties of laser beams:
  - high intensity
  - near monochromaticity
  - high degree of transverse coherence (→ high collimation)
  - high degree of longitudinal/temporal coherence

- how can one use coherence as a discriminating property of scattered laser radiation
  - transverse coherence is easily lost in most scattering processes – hence of not much use
  - temporal coherence is mostly preserved in small-angle scattering

so, can we use temporal coherence in laser-radiation detection?

although - there was a number of proposals and patents, from 1970s until recent years, but, to our knowledge, no practical implementations

the apparent reason: the proposed methods were based on amplitude interferometry (AI)
■ amplitude interferometry (AI) vs. intensity interferometry (II)

comparison of features

amplitude interferometry
rather complex electro-mechano-optical systems, including various combinations of lenses, light modulators, focal-plane arrays, Fabry-Perot etalons, Michelson or Mach-Zehnder-type interferometers (+ electronics)

complex
high-cost
bulky
fragile

intensity interferometry
a system of several fixed light-intensity detectors (e.g., photodiodes) plus an electronic circuit measuring correlations in detectors' photocurrents

simple
low-cost
compact
robust
intensity interferometry (II) – in a nutshell

specifically, the stellar intensity interferometry (SII)

► an ingeniously effective idea pioneered in the 1950s by Robert Hanbury Brown and Richard Quintin Twiss in a series of breakthrough astronomical observations leading to measurements of diameters of distant stars

► many spin-off applications in a variety of fields (X-ray free-electron lasers, nuclear and particle physics, medical imaging)

► active developments up to 1970s then superseded by amplitude interferometry

► recent revival - using clusters of modern telescopes, modern electronics, large baselines, hence improved angular resolution

1964

Flux collectors at Narrabri


32 stellar diameters measured,
0.41mas < D < 3.24mas.
10 of them in the main sequence
The quantity being measured in intensity interferometry is cross-correlation of the fluctuations of the photocurrents of the two detectors, normalized to the product of photocurrent fluctuations measured independently by the two detectors (e.g., photodiodes) located at points \( R \pm \frac{\varphi}{2} \) relative to the source.

\[
C(R, \varphi) := \frac{\langle \Delta J(R + \varphi/2) \Delta J(R - \varphi/2) \rangle}{\sqrt{\langle (\Delta J(R + \varphi/2))^2 \rangle \langle (\Delta J(R - \varphi/2))^2 \rangle}}
\]

\[
\Delta J(R \pm \varphi/2) = J(R \pm \varphi/2) - \langle J(R \pm \varphi/2) \rangle
\]

The normalization preserves correlations and suppresses effects of fluctuations in the individual currents.
stellar intensity interferometry (schematically)

- in stellar II the intensity correlation coefficient \( C(R, \varrho) \) is given, to a good approximation, by

\[
C_{\text{SII}}(R, \varrho) = \frac{\delta F(\varrho)}{1 + \delta} \approx \delta F(\varrho)
\]

(since \( \delta \lesssim 10^{-4} \ll 1 \))

where

- \( \delta \) - count degeneracy parameter
  (number of photoelectrons detected during the radiation's coherence time)

\[
\delta = \frac{1}{2} \Delta \tau A_d \eta \mathcal{E}
\]

\( \Delta \tau \) = radiation’s coherence time  \( A_d \) = detector surface area
\( \eta \) = detector’s quantum efficiency, \( \eta \lesssim 1 \)
\( \mathcal{E} \) = irradiance = number of photons per second per meter squared

- \( \delta \) small in stellar interferometry

- \( F(\varrho) \) - transverse intensity correlation function (proportional to the square of the Fourier transform of the source intensity distribution)

\[
F(0) = 1
\]
\[
F(\varrho) \text{ negligible for } |\varrho| \gtrsim \Delta \varrho = \lambda R/D
\]

\( \Delta \varrho \) - correlation range

\( D \) - transverse source size  \( R \) - observation distance
**SII vs off-axis laser beam detection**

- in SII, the correlation coefficient
  \[ C_{\text{SII}}(\mathbf{R}, \varrho) = \frac{\delta F(\varrho)}{1 + \delta} \approx \delta F(\varrho) \sim \delta \sim 10^{-4} \ll 1 \]

  is small, because the coherence time of star radiation and hence the count degeneracy parameter \( \delta \) are small.

  - goal of SII is to measure the source size (star diameter) \( D \) by finding the correlation range \( \Delta \varrho \) and using
    \[ \Delta \varrho = \lambda R/D \]

  - and, astronomers have plenty of time and measurements may take many hours

- in detection of *off-axis laser radiation* we are not interested in the source size, but
  - we have *two types of radiation*, high- and low-coherence
  - we need to *isolate high-coherence radiation* from, possibly, *stronger low-coherence background*
  - we have to do all that *quickly*, hence \( C(\mathbf{R}, \varrho) \) *cannot be small*

  both the II theory and the instrumentation have to be modified.
■ generalization of the II theory to multiple sources

► the approach:

► relate the photocurrents and their correlations to correlation of intensities (photodetection theory)

► relate correlations of intensities to correlations of fields (Gaussian field statistics, valid for radiation from a very large number of scatterers, for both off-axis and diffuse solar radiation)

► relate properties of scattered fields to that of the beam and the solar illumination (especially their coherence times)
generalization of the II theory to multiple sources

- the correlation coefficient:

\[
C(R, \varrho) = \frac{\langle \Delta J(R + \varrho/2) \Delta J(R - \varrho/2) \rangle}{\sqrt{\langle (\Delta J(R + \varrho/2))^2 \rangle \langle (\Delta J(R - \varrho/2))^2 \rangle}} = \frac{\langle \Delta J_+ \Delta J_- \rangle}{\sqrt{\langle (\Delta J_+)^2 \rangle \langle (\Delta J_-)^2 \rangle}}
\]

- photocurrent (electrons per second), according to basic photoelectric effect theory for stationary radiation:

\[
J(t) = \sum_{j=1}^{n} h(t - t_j) = \text{sum of pulses associated with photoelectrons emitted at random time instances } t_j
\]

detector response function

of width \(T_d \gg \Delta \tau\) (“slow detector”)

normalized to \(\int dt \ h(t) = 1\)

- average photocurrent:

\[
\langle J(t) \rangle = \eta \int dt' \ h(t-t') \langle I(t') \rangle
\]

- average photocurrent squared:

\[
\langle (J(t))^2 \rangle = \left\langle \sum_{j=1}^{n} h(t - t_j) \ h(t - t_j) + \sum_{j \neq k=1}^{n} h(t - t_j) \ h(t - t_k) \right\rangle
\]

\[
= \eta \int_{-T/2}^{T/2} dt_1 \ h(t - t_1) \ h(t - t_1) \langle I(t_1) \rangle + \eta^2 \int_{-T/2}^{T/2} dt_1 \ dt_2 \ h(t - t_1) \ h(t - t_2) \langle I(t_1) I(t_2) \rangle
\]

shot-noise contribution
generalization of the II theory to multiple sources

- the correlation coefficient:

\[ C(R, \varrho) = \frac{\langle \Delta J_+ \Delta J_- \rangle}{\sqrt{\langle (\Delta J_+)^2 \rangle \langle (\Delta J_-)^2 \rangle}} \]

- the numerator:

\[ \langle \Delta J_+ \Delta J_- \rangle = \eta^2 \int dt_1 dt_2 h(t_0 - t_1) h(t_0 - t_2) \langle \Delta I_+(t_1) \Delta I_-(t_2) \rangle \]

\[ \approx \eta^2 \int dt' h^2(t') \int d\tau \langle \Delta I_+\left(\frac{\tau}{2}\right) \Delta I_-\left(-\frac{\tau}{2}\right) \rangle = \frac{\eta^2}{T_d} \int d\tau \langle \Delta I_+\left(\frac{\tau}{2}\right) \Delta I_-\left(-\frac{\tau}{2}\right) \rangle \]

arbitrary reference time

slow-detector assumption and stationarity:

\[ \langle \Delta I_+(t_1) \Delta I_-(t_2) \rangle \]

depends only on \( t_1 - t_2 = \tau \)

- factors in the denominator:

\[ \langle (\Delta J_\pm)^2 \rangle = \eta \int dt' h^2(t_0 - t') \langle I_\pm \rangle + \eta^2 \int dt_1 dt_2 h(t_0 - t_1) h(t_0 - t_2) \langle \Delta I_\pm(t_1) \Delta I_\pm(t_2) \rangle \]

\[ \approx \frac{\eta}{T_d} \langle I_\pm \rangle + \frac{\eta^2}{T_d} \int d\tau \langle \Delta I_\pm\left(\frac{\tau}{2}\right) \Delta I_\pm\left(-\frac{\tau}{2}\right) \rangle \]

shot-noise contribution
generalization of the II theory to multiple sources

- use Gaussian statistics of the field to express correlation of intensities in terms of correlation of fields:

\[
\langle \Delta I_+ \left( \frac{\tau}{2} \right) \Delta I_- \left( -\frac{\tau}{2} \right) \rangle \equiv \langle \Delta I \left( \frac{\tau}{2}, R + \frac{\varrho}{2} \right) \Delta I \left( -\frac{\tau}{2}, R - \frac{\varrho}{2} \right) \rangle = \frac{|\Gamma(\tau; R, \varrho)|^2}{2}
\]

correlation function of the field \(u\) (a component of the electric field) at two different time instances and spatial points

\[
\Gamma(\tau; R, \varrho) := \langle u \left( t + \frac{\tau}{2}, R + \frac{\varrho}{2} \right) u^* \left( t - \frac{\tau}{2}, R - \frac{\varrho}{2} \right) \rangle = \Gamma(0; R, \varrho) \gamma(\tau)
\]

intensity at the observation point \(R\)

- evaluate fields and their correlation \(\Gamma(\tau; R, \varrho)\) in Fresnel approximation for a source of transverse size \(D\):

\[
|\Gamma(0; R, \varrho)|^2 \approx |\Gamma(0; R, 0)|^2 F(\varrho) \quad \text{function of width} \quad \Delta \varrho \sim \frac{\lambda R}{D}
\]

\[
F(0) = 1
\]

The physical mechanism behind the estimate of \(\Delta \varrho\):
Radiation of points within the source results in destructive interference (due to large phase variations) outside the cone of the Rayleigh angle \(\sim \lambda/D\).
The diameter of that cone at the distance \(R\) is \(\lambda R/D \sim \Delta \varrho\).
generalization of the II theory to multiple sources

the correlation coefficient:

\[ C(R, \varrho) = \frac{\langle \Delta J_+ \Delta J_- \rangle}{\sqrt{\langle (\Delta J_+)^2 \rangle \langle (\Delta J_-)^2 \rangle}} \]

result for the numerator:

\[ \langle \Delta J_+ \Delta J_- \rangle = \frac{\eta^2}{2T_d} A_d^2 \mathcal{E}^2 \int_{\tau} d\tau \left| \gamma(\tau) \right|^2 F(\varrho) = \frac{\eta}{T_d} A_d \mathcal{E} \delta F(\varrho) \]

\[ \delta := \frac{1}{2} \Delta \tau A_d \mathcal{E} \]

result for the denominator:

\[ \sqrt{\langle (\Delta J_+)^2 \rangle \langle (\Delta J_-)^2 \rangle} = \frac{\eta}{T_d} A_d \mathcal{E} + \frac{\eta^2}{2T_d} A_d^2 \mathcal{E}^2 \Delta \tau = \frac{\eta}{T_d} A_d \mathcal{E} (1 + \delta) \]

final result: in both numerator and denominator add contributions from independent coherent (c) and background (b) sources:

\[ C(R, \varrho) = \frac{\delta_c \mathcal{E}_c F_c(\varrho) + \delta_b \mathcal{E}_b F_b(\varrho)}{(1 + \delta_c) \mathcal{E}_c + (1 + \delta_b) \mathcal{E}_b} \]
generalization of the intensity correlation coefficient to two types of radiation – summary

\[ C(R, q) := \frac{\langle \Delta J(R+q/2) \Delta J(R-q/2) \rangle}{\sqrt{\langle (\Delta J(R+q/2))^2 \rangle \langle (\Delta J(R-q/2))^2 \rangle}} \]

▲ SII (low-coherence thermal radiation)

\[ C_{\text{SII}}(q) = \frac{\delta F(q)}{1 + \delta} \]

▲ generalization to two types of radiation (“coherent” (c) and “background” (b))

\[ C(R, q) = \frac{\delta_c \mathcal{E}_c F_c(q) + \delta_b \mathcal{E}_b F_b(q)}{(1 + \delta_c) \mathcal{E}_c + (1 + \delta_b) \mathcal{E}_b} \]

$F(q)$ - transverse intensity correlation function
(normalized square of the Fourier transform of the source intensity distribution)

$\mathcal{E}$ - irradiance, # of photons per second per meter squared

$\delta = \frac{1}{2} \Delta \tau \Lambda_d \eta \mathcal{E}$ - detection degeneracy parameter, # of photoelectrons per coherence time
assessment of the temporal coherence and irradiance in off-axis laser radiation

- laser beam scattering in the medium acts as a secondary radiation source
- radiation arriving at the detector travels different-length paths depending, for a given scattering angle $\vartheta$, on the point in the beam from which it was emitted
- however, the beam can be approximately modeled as a set of mutually uncorrelated coherently radiating sources (segments)
assessment of the temporal coherence and irradiance in off-axis laser radiation

► effective source size

- segment length $\Delta z$ is determined from the condition for the maximum path length difference not exceeding the coherence length:

$$
\left( \text{blue path} - \text{magenta path} \right) \approx \frac{\vartheta^2 \Delta z}{2} \lesssim c \Delta \tau_c
$$

$$
\Rightarrow \Delta z \approx \frac{2c \Delta \tau_c}{\vartheta^2} \approx 48 \text{ m} \quad \text{(assuming a reasonable coherence length } c \Delta \tau_c = 6 \text{ cm)}
$$

- segment size in the beam plane, as seen from the detector, is $D_{\parallel} \approx \vartheta \Delta z \approx 2.4 \text{ m}$

- segment size normal to the beam plane is the beam diameter, say, $D_{\perp} \approx 10 \text{ cm}$

► off-axis irradiance

- assuming total beam power 250 kW and attenuation length 1 km, energy radiated from the beam segment is:

$$
\frac{48 \text{ m}}{1 \text{ km}} \times 250 \text{ kW} = 12 \text{ kW}
$$

- irradiance at the detector (assuming isotropic scattering):

$$
\mathcal{E}_c = \frac{12 \text{ kW}}{4\pi R^2} \approx 4 \cdot 10^{-3} \frac{\text{W}}{\text{m}^2} \approx 3 \cdot 10^{16} \frac{\text{photons}}{\text{s m}^2}
$$

(a pessimistic assumption, since scattered radiation will be likely collimated along the beam)
\[ C(\varphi) = \frac{\delta_c \mathcal{E}_c F_c(\varphi) + \delta_b \mathcal{E}_b F_b(\varphi)}{(1 + \delta_c) \mathcal{E}_c + (1 + \delta_b) \mathcal{E}_b} \]

**coherent signal**

- transverse intensity correlation distribution: \( F_c(\varphi) \)
- transverse source size: \( D_{c\perp} \lesssim 10 \text{ cm} \)
- transverse correlation range: \( \Delta \varphi_{c\perp} \sim \frac{\lambda R}{D_{c\perp}} \sim 1 \text{ cm} \)
- irradiance: \( \mathcal{E}_c \sim 10^{16} \)
- coherence time, length: \( \Delta \tau_c \sim 0.2 \text{ ns}, c \Delta \tau_c \sim 6 \text{ cm} \)
- detection degeneracy parameter: \( \delta_c \sim \frac{1}{2} \Delta \tau_c A_d \mathcal{E}_c \sim 10 \)

**incoherent background**

- transverse intensity correlation distribution: \( F_b(\varphi) \)
- transverse source size: \( D_b = \text{“\infty”} \) (a very large area of the sky)
- transverse correlation range: \( \Delta \varphi_b \sim \frac{\lambda R}{D_b} \sim 10 \mu m \)
- irradiance: \( \mathcal{E}_b \sim 10^{19} \)
- coherence time, length: \( \Delta \tau_b \sim 10 \text{ fs}, c \Delta \tau_b \sim 3 \mu m \)
- detection degeneracy parameter: \( \delta_b \sim \frac{1}{2} \Delta \tau_b A_d \mathcal{E}_b \sim 0.5 \)

\[ 1 \text{ W} \leftrightarrow 7.5 \times 10^{18} \frac{\text{photons}}{\text{s}} \]

**note:** at \( \lambda = 1.5 \mu m \)
estimate of admissible background irradiance

\[ C(\varrho) = \frac{\delta_c \mathcal{E}_c F_c(\varrho) + \delta_b \mathcal{E}_b F_b(\varrho)}{(1 + \delta_c) \mathcal{E}_c + (1 + \delta_b) \mathcal{E}_b} \]

- very short transverse correlation range of the background
  \[ \Delta \varrho_c \gg \Delta \varrho_b \]
  \[(1 \text{ cm} \gg 10 \mu \text{m}) \implies F_b(\varrho) \approx 0 \text{ for any feasible distance } \varrho \text{ between the photodiodes} \]

- small background degeneracy parameter \( \delta_b \ll 1 \)

\[ C(\varrho) \approx \frac{\delta_c \mathcal{E}_c F_c(\varrho)}{(1 + \delta_c) \mathcal{E}_c + (1 + \delta_b) \mathcal{E}_b} \approx \frac{\delta_c F_c(\varrho)}{1 + \delta_c + \mathcal{E}_b / \mathcal{E}_c} \]

shot noise

possibly large background-to-signal ratio

background-to-signal ratio may be large but so is the signal degeneracy parameter \( \delta_c \gg 1 \)
so the observed intensity correlation coefficient may remain close to one
estimate of admissible background irradiance

\[
C(\varrho) = \frac{\delta_c \, F_c(\varrho)}{1 + \delta_c + \mathcal{E}_b/\mathcal{E}_c}
\]

- signal degeneracy parameter depends on the irradiance, \( \delta_c \sim \frac{1}{2} \Delta \tau_c \, A_d \, \mathcal{E}_c \), hence

\[
C(\varrho) = \frac{F_c(\varrho)}{1 + \frac{\mathcal{E}_d}{\mathcal{E}_c} \left(1 + \frac{\mathcal{E}_b}{\mathcal{E}_c}\right)}
\]

where

\[
\mathcal{E}_d := \frac{2}{\Delta \tau_c \, \eta \, A_d}
\]
detector’s “characteristic irradiance” (photons per sec per square meter) dependent only on \( \Delta \tau_c \) and detector’s parameters

- for \( \Delta \tau_c = 0.2 \text{ ns}, \eta = 0.5, A_d = 10 \text{ mm}^2 \):

\[
\mathcal{E}_d = 2 \cdot 10^{15} \frac{\text{photons}}{\text{s m}^2} \approx 3 \cdot 10^{-4} \frac{\text{W}}{\text{m}^2}
\]

for a given coherence time, \( \mathcal{E}_d \) can be reduced by increasing \( \eta \) and \( A_d \) lower \( \mathcal{E}_d \) means a higher detection sensitivity
estimate of admissible background irradiance – main result

- normalized intensity correlation coefficient within the correlation range \( \Delta \varphi_{c\perp} \sim \lambda / D_{c\perp} \approx 1 \text{ cm} \):

\[
C(\varphi) \approx \frac{1}{1 + \frac{\mathcal{E}_d}{\mathcal{E}_c} \left( 1 + \frac{\mathcal{E}_b}{\mathcal{E}_c} \right)} \approx \frac{1}{1 + \frac{\mathcal{E}_d \mathcal{E}_b}{\mathcal{E}_c^2}}
\]

- generally, if we can measure \( C(\varphi) \geq C_0 \), we can tolerate background up to the level

\[
\frac{\mathcal{E}_b}{\mathcal{E}_c} \leq \frac{1 - C_0}{C_0} \frac{\mathcal{E}_c}{\mathcal{E}_d}
\]

- with \( C_0 = 0.1 \) and the two parameters found above,

\[
\mathcal{E}_c = \frac{12 \text{ kW}}{4\pi R^2} \approx 4 \cdot 10^{-3} \frac{\text{W}}{\text{m}^2} \approx 3 \cdot 10^{16} \frac{\text{photons}}{\text{s} \text{m}^2}
\]

\[
\mathcal{E}_d = 3 \cdot 10^{-4} \frac{\text{W}}{\text{m}^2} = 2 \cdot 10^{15} \frac{\text{photons}}{\text{s} \text{m}^2} \ll \mathcal{E}_c
\]

off-axis radiation is detectable up to the background level \( \frac{\mathcal{E}_b}{\mathcal{E}_c} \approx 135 \)

sufficiently small value of the detector’s characteristic irradiance \( \mathcal{E}_d \) allows identification of off-axis laser radiation even in the presence of a much stronger background
A possible detector design concept

“Top view” of the detector system

- Amplifiers
- Photo-diodes
- Lenslets
- Correlated currents

Expected correlation of current fluctuations in the photodiodes

Beam in overlapping fields-of-view of two photodiodes
a possible detector design concept

“front view” of the detector system

► a composite-eye set of lenslets and photodiodes
► fields of view (FOVs) of photodiodes partly overlap, such that every point in view is seen by at least two photodiodes
► near-neighbor photodiodes are connected by a network of amplifiers and “correlators”

the beam as seen from the detector

► suppose the beam is (or would be) seen as a horizontal line
– what is the spatial distribution $F_c(\varrho)$ of intensity correlations?

$$D_\perp = 10 \text{ cm}$$
$$D_\parallel = 2.4 \text{ m}$$

$F_c(\varrho)$

radiation source = coherent beam segment

Fourier transform of the source intensity distribution

$\Delta \varrho_\parallel \approx \frac{\lambda R}{D_\parallel} \approx 0.3 \text{ mm}$

$\Delta \varrho_\perp \approx \frac{\lambda R}{D_\perp} \approx 7.5 \text{ mm}$

$F_c(\varrho) \approx 0$

$F_c(0) = 1$
**a possible detector design concept**

**detector system looking in the direction of the beam**

- For an arbitrary beam direction, the spatial distribution of correlations, $F_c(\mathbf{q})$, will be very narrow in the beam plane and wider in the perpendicular direction.

- Expected current correlations:
  - Expected correlations in currents of some nearest-neighbor photodiodes in the direction approximately normal to the beam plane.
  - Correlations in the direction parallel to the beam plane have very short ranges (smaller than photodiode spacing) and are unobservable.

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AFOSR EM review 2022
summary

► We described an approach for detecting off-axis radiation of a high-energy laser beam.

► The proposed detector takes advantage of the high temporal coherence of the off-axis radiation in order to isolate it from a possibly much stronger but low-coherence background.

► Since radiation coherence is detected by means of intensity-interferometry methods, the detecting system should be simple, low-cost, small, light, and robust.

► Further developments:
  
  – possible further sensitivity improvement through alternative coherence measurement methods, different from measuring the conventional normalized correlation coefficient

  – extension of the method to detection of pulsed beams (II for nonstationary radiation)

  – application of similar coherence detection methods in laser-warning systems and in active imaging systems in which illumination is provided by a laser beam - primarily LiDAR - especially in “degraded visibility environments”
THANK YOU!