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Re-interpreting "coherence" in light of Non-Interaction of Waves, or the NIW-Principle

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ABSTRACT

The autocorrelation, or the Wiener-Khintchine, theorem plays a pivotal role in optical coherence theory. Its proof derives from the time-frequency Fourier theorem. The derivation requires either dropping the cross-products (interference terms) between the different filed amplitudes corresponding to different frequencies, or taking time integration over the entire duration of the signal. The physical interpretation of these mathematical steps implies either (i) non-interference (non-interaction) between different frequencies, or (ii) the registered data is valid for interpretation when the detector is set for long time integration. We have already proposed the generic principle of Non-Interaction Waves (NIW), or absence of interference between light beams. The hypothesis of non-interaction between different frequencies was used by Michelson to frame the theory behind his Fourier Transform Spectroscopy, which is correct only when the detector possesses a long integrating time constant like a human eye, a photographic plate, or a photo detector circuit with a long LCR time constant. A fast detector gives heterodyne signal. So, the correlation factor derived by the prevailing *coherence* theory, and measured through fringe visibility, is essentially the quantum property of the detecting molecules compounded by the rest of the follow-on instrumentation. Low visibility fringes (low correlation factor) does not reflect intrinsic property of light alone; it is a light-matter joint response characteristics. So, we re-define *coherence* by directly referring to the key characteristics of light beams being analyzed as: (i) *spectral correlation* (presence of multi frequency), (ii) *temporal correlation* (time varying amplitude of light), (iii) *spatial correlation* (independent multi-point source), and (iv) *complex correlation* (mixture of previous characteristics).

Keywords: Coherence; Optical correlation; NIW-principle; Spectral correlation; Temporal correlation; Spatial correlation; Complex correlation.

1. INTRODUCTION

Detectors determine what we measure. We *see* light only through the *eyes* of the detectors! A detector can neither gather all the information about the stimulant it is *detecting*, nor can it deliver that limited information with 100% fidelity to our recorders, since our instruments are always *band-limited*. This is a *Perpetual Information Challenge (PIC)*, a natural constraint that we must learn to overcome by iteratively improving all of our working theories as our knowledge advances and technology improves for more complex and precise measurements. The approach would require focusing on the interaction processes and information gathering processes and iteratively keep on improving our current and future working theories.

1.1. Detectors determine the superposition effects - developing the rationale further

Our starting platform is the semi-classical model for light-matter interaction processes: space and time finite wave packet interacts with quantized atoms [1,2]. Propagation characteristics of light is modeled quite successfully from the most macro to nano distances, from predicting coherence properties of the Sun & star lights to accurately modeling nano photonics devices, using Huygens-Fresnel diffraction integral and Maxwell's wave equation. None of these modeling require propagation of indivisible photons. Such attempts only introduces non-causal hypotheses.

1.1.1. We are underscoring the need for interaction process mapping epistemology (IPM-E): All measured data are results of physical transformations experienced by interactants through energy exchange due to physical interaction process guided by some allowed force of interaction between them. The prevailing measurable data modeling epistemology (MDM-E) is not sufficient to advance physics, although it is a critically necessary step [3,4].

1.1.2. We are adding a new phenomenon, the NIW-Principle (Non-Interaction of Waves) in the linear domain: Waves, which are propagating undulations in some physical tension field, pass through each other unperturbed in the linear domain, as there are no forces of interaction between them. Thus waves cannot interfere by themselves. Superposition effects of multiple waves become manifest only in the presence of some suitable material that can interact with all the superposed fields simultaneously [5,6,7].

1.1.3. The last two assumptions lead to re-interpretation of the *coherence* phenomenon: Currently *coherence* is theorized as the normalized correlation between two superposed beams. But beams by themselves cannot help us quantify the field-field correlation, or the mutual phase relationship, since they do not interact with each other (NIW-principle).

Correlation is measured as fringe visibility registered by detectors as transformation in them. A detector's (i) quantum properties and (ii) the time of integration during which it absorbs energy from all the superposed waves, dictate the fringe visibility. Thus, the measured fringe visibility reflects these two properties of the detector while the superposed waves assist in providing the energy, restricted by the quantum rules and the energy processing time-constant of the system, as a whole. The relative phases of the incident waves, which simultaneously stimulate the detectors, are critical parameters because the QM recipe for the transfer of energy from all the stimulating fields depend upon the square modulus of the sum of all the complex amplitude stimulations experienced by the detector.

Light is never *incoherent* by itself. All wave packets are individually phase-steady collective phenomenon. Joint stimulations simultaneously induced on a detector by multiple superposed wave groups, averaged over a time period, will vary, based on the integration time. Thus, an atto-second detector will find all light *coherent* if they consist of wave packets of duration of femto second or longer.

In this paper we will be defining *coherence* as various conditional correlations (visibilities) directly relevant to the specific physical parameters of light being analyzed:

(i) *Spectral correlation* (light with frequency variation).
(ii) *Temporal correlation* (light with amplitude variation).
(iii) *Spatial correlation* (light with independent multiple emitters).
(iv) *Complex correlation* (mixture of the above cases).

In section-2 we present the logics behind inevitability of the NIW-principle, which is supported by quoting a 1976 experiment. Section-3 develops the concepts behind spectral correlation. Section-4 develops the concepts behind temporal correlation. Section-5 develops the concepts behind spatial correlation. Section-6 develops the concepts behind complex correlation.

2. APPRECIATING THE NIW-PRINCIPLE

2.1. The NIW-principle from pure logics of Interaction Process Mapping Epistemology (IPM-E)

Debates, dominantly between Bohr and Einstein, regarding the interpretation of Quantum Mechanics (QM) identified a serious *Measurement Problem* [8], which we believe arises because our the detectors can never provide us with all the information about the interactants participating in our measuring instrument. We have briefly introduced this concept in the introduction as the existence of perpetual information challenge (PIC). If we use IPM-E to construct a logical flow chart as to how measurable data arise, we can discover many subtle but very important issues regarding measurements as well as the NIW-principle and its corollary that time-frequency Fourier theorem cannot be a generic principle of nature.

Our point can be illustrated mathematically as follows. Suppose we have N superposed light beams passing through a well defined spatial volume. The effect of superposition can become manifest only if we insert a suitable detector within the volume of physical superposition. In the absence of any detector, the light beams will simply pass through completely unperturbed by each other. The detector's response can be represented by the energy absorbed by it which is the square modulus of all the N-simultaneous amplitude stimulations experienced by it, $\chi(\nu)$ being the polarizability of the detecting molecules, which would be a constant for a narrow band of light:

$$D_\Sigma = \Psi\Psi^* = \left|\sum\nolimits_m \chi(\nu)E_m(\nu)\right|^2 = \chi^2\left|\sum\nolimits_m E_m(\nu)\right|^2 \tag{1}$$

Because of our mathematical rule, we can take the frequency independent χ^2 out of the summation sign and then we are left with the square modulus of the electric fields only. We thus deceive ourselves as if the EM waves sum themselves and then they carry out the physical process square-modulus and re-distribute their energies all by themselves! There are no known forces of interaction between EM waves that can facilitate these two physical processes, (i) summing the field amplitudes, and (ii) carrying out the square modulus process! We have been assigning the jobs that are done by the quantized detectors on to the fields. Accordingly, we have been forced to assign the observed quantized characteristics in our data as due to fields being quantized! χ^2 is not just a *mere* detector constant, $\chi(\nu)$ is behind the core physical process of summing all the simultaneous dipole stimulations induced by all the EM waves.

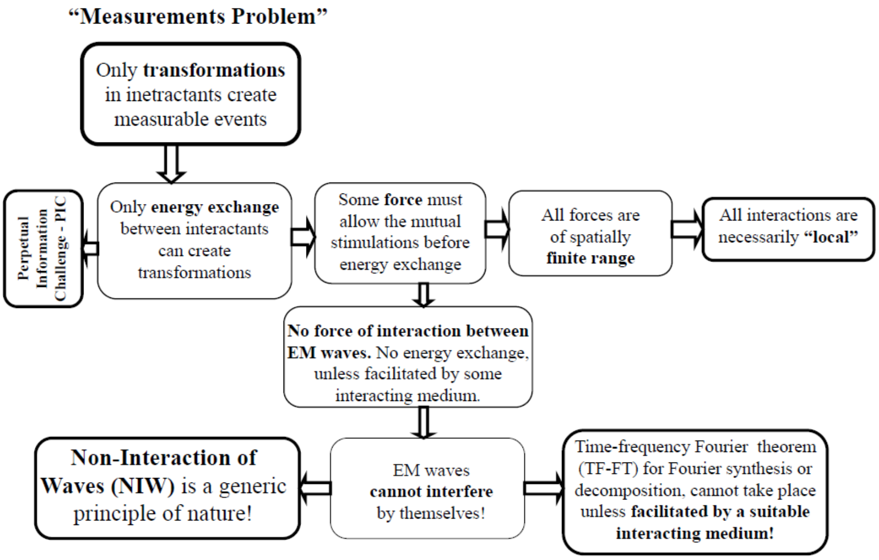


Figure 1. Flow chart describes logical steps behind any generic measurement process. Any measurable transformation requires energy exchange between the interactants facilitated by an allowed force. Since propagating waves by themselves do not exert any force on each other, they cannot interact or interfere in the absence of some interacting medium.

2.1. The NIW-principle from a simple experiment

Figure 2 shows a pair of parallel beam splitters, also known as a Fabry Perot interferometer (FPI), tilted with respect to the incident beam and receiving a collimated He-Ne laser beam running in two longitudinal modes (frequencies). The FPI produces a set of parallel beams, which is made to converge on a one-sided ground glass. Flat front surface towards the FPI sends out the convergent beams as a new divergent set of beams as if reflection from the flat surface does not allow them to experience each other, or interfere with each other! The silica molecules in the flat surface present a collective change in the boundary refractive index value and all the focused wave fronts are reflected independent of each other, preserving their respective Poynting vectors. But the silica clusters, comparable to the size of the wave length, from the ground-glass surface (away from the FPI) interacts with all the incident light beams and facilitates spectral energy separation leveraging superposition effect. The enlarged image of the ground glass surface gives spectrally resolved fringes for the laser modes [9,10]. The locations where the electric vectors arrive in phase, the silica clusters scatters light strongly and help generate bright fringes when imaged by our eye or a lens. The locations where the resultant stimulation due to the light beams is zero, silica clusters do not produce forward scattering, and we observe a dark fringe. Bright and dark fringes are not due to arrival, or non-arrival of photons, respectively.

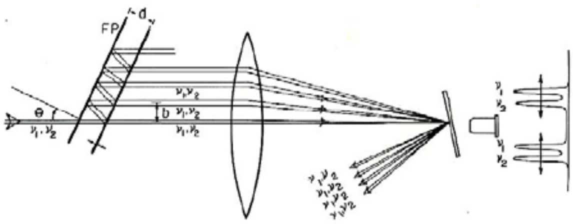


Figure 2. A tilted, but parallel, pair of beam splitters generates a set of parallel replicated beams from a single incident laser beam. These beams are then made to converge on a one-sided ground glass. The unperturbed (un-interfered) reflection takes place from the flat surface and superposition frinfges are generated by the ground-glass surface [9].

3. SPECTRAL CORRELATION

3.1. Is white light "incoherent"?

If we pay close attention to the physical process behind the formation of fringes due to multi frequency light under analysis, we will realize that the reduction in visibility is due to the sum of many perfect visibility fringes displaced due to changes in the order of *interference* m as the relative time delay τ changes. For the same delay τ the order of interference changes for different frequencies. This conclusion is valid when we record time integrated fringes:

$$m = \nu\tau = \nu.(\Delta / c) = \Delta / \lambda; \quad \Delta \text{ being the realtive path delay.} \qquad (2)$$

Inspite of such fringe displacements, one can still register excellent visibility fringes using white light for order of interference $m \equiv \nu\tau \leq 2$. Yet, we tend to define white light as the most *incoherent* light!

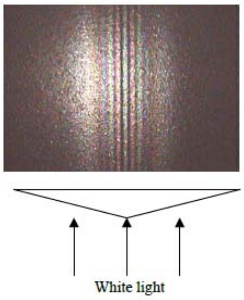
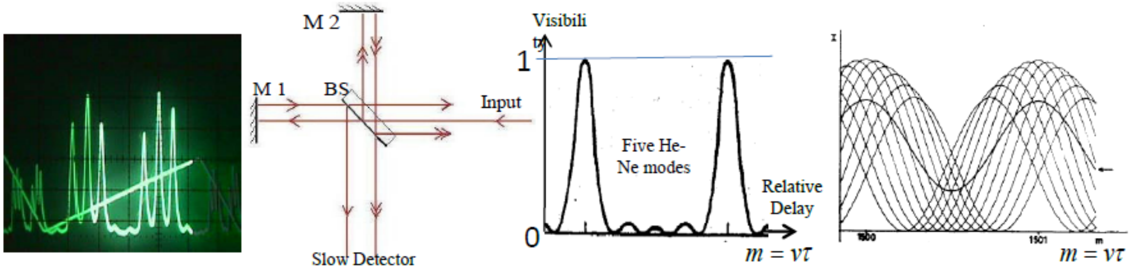


Figure 3. White light can produce quite high quality fringes using a simple Fresnel bi-prism. Is white light really incoherent, or there are some other deeper physics behind degradation of fringe visibility? (Photo taken from the web).

3.2. Is a CW multi mode He-Ne laser intrinsically incoherent?

Consider a 48cm CW He-Ne laser cavity. Its relative mode strength is given in Fig.2a. If one measures the fringe visibility using a Michelson interferometer as in Fig2b [11], it would look somewhat like that shown in Fig.2c, periodically reaching unity with $\tau = n(2L / c) = n / \delta\nu$, where n is an integer, L is the laser cavity length and $\delta\nu$ is the mode spacing.

The reduction in the visibility can be appreciated as the sum of many displaced high visibility fringes, as shown in Fig.2d. The key technical point to recognize is that the axis that account for the fringe location is really the interference order axis, $m = \nu\tau$. The degradation of fringe visibility is not because the individual laser modes are incoherent to each other. Further, such data is valid only for slow, time integrating detector, as will be explained soon.



(a) (b) (c) (d)

Figure 4. Multi-longitudinal mode He-Ne laser modes, as in (a), passing through a Michelson interferometer, as in (b), can produce oscillatory fringe visibility, as in (c), because of sum of intensities due to perfect visibility fringes due to different frequencies that are translated with respect to each other, as in (d). (from ref. 11).

3.3. Frequency-Delay Fourier Transform (FD-FT). Invention of Fourier transform spectrometry!

Consider an ideal CW laser running in N modes of equal strength with amplitude spectrum $s(\nu)$ and the spectral distribution function as:

$$S(\nu) = \sum_{n=0}^{N-1} \delta(\nu - \nu_n) \qquad (3)$$

Let us analyze this light by sending the laser beam through a Michelson interferometer, as shown in Fig.4b. The detector signal can be derived, as in Eq.4, following Michelson's assumption that different optical frequencies do not interfere, which is true when the detector is a time integrating one. Mathematically, the cross terms $m \neq n$ in the product of Eq.3 are considered zero:

$$\begin{aligned} D_\Sigma(\tau) &= \left[\sum\nolimits_{n=0}^{N-1}\{\chi e^{i2\pi\nu_n t} + \chi e^{i2\pi\nu_n(t+\tau)}\}\right]^* \left[\sum\nolimits_{m=0}^{N-1}\{\chi e^{i2\pi\nu_m t} + \chi e^{i2\pi\nu_m(t+\tau)}\}\right] \\ &= \chi^2 \sum\nolimits_{n=0}^{N-1}\left|e^{i2\pi\nu_n t} + e^{i2\pi\nu_n(t+\tau)}\right|^2 = 2\chi^2\sum\nolimits_{n=0}^{N-1}[1+\cos 2\pi\nu_n\tau] \end{aligned} \tag{4}$$

The result is a sum of translated set of cosine fringes on a DC background! Michelson's brilliant mind recognized that if he removes the DC signal from the data extracts only the normalized oscillatory terms, he can extract the frequency information by Fourier transforming the left over oscillatory signal:

$$D_{osc.}(\tau) = \sum\nolimits_{n=0}^{N-1}\cos 2\pi\nu_n\tau \equiv \gamma_\nu(\tau) \tag{5}$$

Of course, the frequency-delay Fourier transform (FD-FT) of Eq. 5 gives the spectral density function of Eq.3, which we started with. The normalized oscillatory visibility is the spectral correlation function $\gamma_\nu(\tau)$. Thus this $\gamma_\nu(\tau)$ and $S(\nu)$ form a Fourier transform pair and is known in literature as the autocorrelation theorem (ACT) [12], derived here somewhat heuristically to underscore the physical origin of the spectral correlation and visibility degradation, to distinguish it from temporal correlation $\gamma_t(\tau)$, to be discussed in the next section. Traditional literature does not distinguish between spectral and temporal correlation, as if they are physically same, as the mathematical derivation of the ACT implies [12].

3.3.1. Invention of Heterodyne spectroscopy: High speed detectors for the optical range were invented in late 1950's[13]. Today they are easily available at a modest cost. Consider first a two mode laser beam is directly shining on such a fast detector. Then the photo detector current will consist of a sinusoidally oscillating current at the difference frequency over a DC bias:

$$D_\Sigma(t) = \left|\chi a e^{-i2\pi\nu_1 t} + \chi a e^{-i2\pi\nu_2 t}\right|^2 = 2\chi^2 a^2[1+\cos 2\pi(\nu_1-\nu_2)t] \tag{6}$$

A slow detector will integrate the oscillating cosine current term to zero leaving the average DC current as:

$$\bar{D}_\Sigma(t) = \int\left|\chi a e^{-i2\pi\nu_1 t} + \chi a e^{-i2\pi\nu_2 t}\right|^2 dt = 2\chi^2 a^2 \tag{7}$$

If we have a laser with N modes with mode spacing $\delta\nu$ on a fast detector, then the normalized signal will consist of summation of all possible sinusoidal difference frequencies given by Eq.8, which will be recognized by an electronic spectrum analyzer (ESA) as a series of $p\delta\nu$ lines after blocking the DC signal. Fig.5 shows the ESA frequency lines $p\delta\nu$ for a five mode He-Ne laser whose spectrum is shown in Fig.4a.

$$D_\Sigma(t) = \left|\sum\nolimits_{-(N-1)/2}^{+(N-1)/2}\frac{\chi}{N}e^{i2\pi(\nu_0+n\delta\nu)t}\right|^2 = \frac{2\chi^2}{N^2} + \frac{2\chi^2}{N^2}\sum_{p=1}^{N-1}(N-p)\cos[2\pi p\delta\nu t] \tag{8}$$

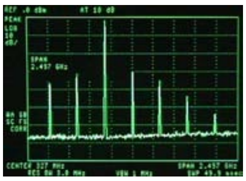


Figure 5. Display of heterodyne difference frequencies extrcated by an electronic spectrum analyzer (ESA). out of the electrical signal from a fast detector given by the Eq.8. due to a 5-mode He-Ne laser. ESA's are designed to reject the DC signal, the first term of Eq.8.

Eq.6 and Eq.7help us appreciate that the same superposed beams can produce different effects depending upon the speed of the detectors. Eq.7 corroborates Michelson's observed data that "different frequencies do not interfere"; but the reality lies with the speed of the detectors. FD-FT, or frequency-delay Fourier transform spectroscopy works because the theory matches the data under time integrated detection and some mathematical manipulation. Light beating spectroscopy helps us understand this better. If we replace the slow detectors in any modern FD-FT spectrometry instrument with a fast detector and fast electronics before the commercial signal analyzing software, the output results will be very confusing to interpret! Our proposed NIW-principle, guided by the Interaction Process Mapping Epistemology (IPM-E), helps us appreciate the deeper light-matter (detector) interaction processes and understand the physics better.

4. TEMPORAL CORRELATION

To appreciate the physical processes behind degradation of fringe visibility due to time varying amplitudes, let us consider an isolated pulse $a(t)$, which is replicated by a Michelson or a Mach-Zehnder interferometer into two relatively delayed pulses $a_1(t)$ and $a_2(t-\tau)$ and superposed on a detector. The carrier frequency is a single frequency. We are not propagating Fourier frequencies of the temporal envelope as those frequencies are not physical. The resultant time varying fringe visibility can be appreciated from the two diagrams in Fig.6. If we now use a time integrating detector, the resultant variation of the visibility (correlation) with interferometer delay τ will be the envelope function of the high frequency fringe (black hash). Mathematical detailed steps are given in Eq.9, where the detector's polarizability factor χ has been omitted for writing convenience. But χ is presented explicitly in the definition of the temporal correlation function in Eq.10 to underscore that because of the normalization process and our mathematical rule of eliminating the same constant from the numerator and the denominator, $\gamma_t(\tau)$ appears to be a correlation of fields only. That the detector carries out the summation implied by the superposition principle is lost by our mathematical rule!

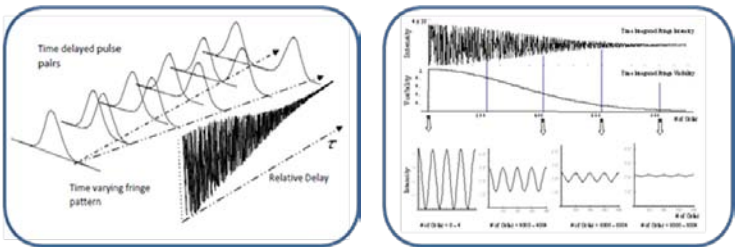


Figure 6. The above two computer generated cartoons help us visualize how the visibility of fringes vary with time due to superposition of different amplitudes as a pair of replicated pulses are ssuperposed repeatedly with different path delays. The time integrated visibility represents the measured and modeled autocorrelation function [11]:

$$
\begin{aligned}
D(t,\tau) &= \int \chi^2 I(t,\tau)\, dt = \int \left| \chi a_1(t) e^{i2\pi\nu t} + \chi a_2(t-\tau) e^{i2\pi\nu(t-\tau)} \right|^2 dt \\
&= \chi^2 \int |a_1(t)|^2 dt + \chi^2 \int |a_2(t-\tau)|^2\, dt + 2\chi^2 \cos 2\pi\nu\tau \int a^*_1(t) a_2(t-\tau)\, dt \\
&= \chi^2 E_1 + \chi^2 E_2 + 2\chi^2 \sqrt{E_1}\sqrt{E_2}\,\gamma_t(\tau)\cos 2\pi\nu\tau \\
&= \chi^2 (E_1 + E_2)[1 + \beta\gamma_t(\tau)\cos 2\pi\nu\tau]; \quad V(t,\tau) \equiv \beta\gamma_t(\tau); \ \beta \equiv 2\sqrt{E_1}\sqrt{E_2}\,/\,(E_1+E_2) = 1 \text{ for } E_1 = E_2
\end{aligned}
\tag{9}
$$

$$
\gamma_t(\tau) = \frac{\int \chi a_1^*(t) \chi a_2(t-\tau) dt}{\left[\int |\chi a_1(t)|^2\, dt\right]^{1/2} \left[\int |\chi a_2(t)|^2\, dt\right]^{1/2}} = \frac{\int a_1^*(t) \chi a_2(t-\tau) dt}{\left[\int |a_1(t)|^2\, dt\right]^{1/2} \left[\int |a_2(t)|^2\, dt\right]^{1/2}}
\tag{10}
$$

4.1. Traditional proof of the Wiener-Khintchine theorem (WKT)

Many a time when some mathematics works to match the observed data, it is worth trying to investigate deeper to ascertain whether the mathematical steps can help us visualize the invisible interaction processes that gave rise to the measurable data. We believe this the case with the WKT. The traditional WKT tells us that $\gamma_t(\tau)$ & $\tilde{A}(f)$ form a Fourier transformation pair, where $\tilde{A}(f)$ represents the Fourier intensity spectrum due to the pulse $a(t)$, such that $a(t)$ and $\tilde{a}(f)$ form a Fourier transform pair and $\tilde{A}(f)$ is the same as $|\tilde{a}(f)|^2$. Below we replicate two standard ways of proving the WKT. Note that we are using the symbol f instead of ν to denote frequency. The is deliberate to underscore that Fourier frequencies f do not represent any physical frequency unlike ν, which we have used in the previous sections where it represented real physical frequency generated by the real sources.

$$\begin{aligned}\gamma_t(\tau) &= \int a^*(t)a(t+\tau)\ dt = \int dt\ \{\int \tilde{a}^*(f)\ e^{2\pi ift} df\}\ \{\int \tilde{a}(f')e^{-2\pi if'(t+\tau)}df'\} \\ &= \int df\ \tilde{a}^*(f) \int df'\ \tilde{a}(f')e^{-2\pi if'\tau} \int dt\ e^{2\pi i(f-f')t} \\ &= \int df\ \tilde{a}^*(f) \int df'\ \tilde{a}(f')e^{-2\pi if'\tau}\delta(f-f') \\ &= \int df\ \tilde{a}^*(f)\tilde{a}(f)e^{-2\pi if\tau} = \int df\ \tilde{A}(f)\ e^{-2\pi if\tau}\end{aligned} \tag{11}$$

Notice the 3rd line of the above Eq.11 where one derives the delta function $\delta(f-f')$. Acting upon this delta function in the next step implies *non-interference* between different frequencies, which was also assumed by Michelson. And we have already demonstrated that such an assumption is erroneous from the stand point of physics, but under time integrated detection, it turns out to match this mathematical model. In fact, the second approach to derive WKT uses this time integration assumption:

$$\begin{aligned}\gamma_t(\tau) &= \int a^*(t)a(t+\tau)\ dt = \int\ a^*(t)\ \left[\int \tilde{a}(f)e^{-2\pi if(t+\tau)}df\right]\ dt \\ &= \int\ \left[\int a^*(t)e^{-2\pi ift}\ dt\right]\ \tilde{a}(f)e^{-2\pi if\tau}df \\ &= \int \tilde{a}^*(f)\tilde{a}(f)e^{-2\pi if\tau}df\ = \int \tilde{A}(f)e^{-2\pi if\tau}df\end{aligned} \tag{12}$$

Note now how the Fourier conjugate variables jumps between $\tau\ \&\ f$ for the WKT and $t\ \&\ f$ for the normal time-frequency transformation of a pulse. Since the variables $t\ \&\ \tau$ are physically unrelated and not the same, there cannot be any physical connection between $\gamma_t(\tau)\ \&\ \tilde{a}(f)$, which is also obvious from our point that Fourier frequencies of a pulse are not physical frequencies present in the signal [14,15]. Jumping back and forth between $\tau\ \&\ f$ and $t\ \&\ f$, as in Eq.12, does not represent consistent logics suitable to explore real physical processes we want to understand.

$$\gamma_t(\tau) \overset{\tau\&f}{\rightleftharpoons} \tilde{A}(f) = \left|\tilde{a}(f)\right|^2 \ ;\quad a(t) \overset{t\&f}{\rightleftharpoons} \tilde{a}(f) \tag{13}$$

In fact, if we replace $\tilde{a}(\nu)\ \&\ \tilde{A}(\nu)$ in the above derivations by the physically real frequency functions $s(\nu)\ \&\ S(\nu)$, then we have the rigorous derivation for the Fourier transform pair $\gamma_\nu(\tau) \rightleftharpoons \tilde{S}(\nu)$, derived heuristically in Section 3.3. It should now be obvious why we have defined two different physical correlation functions, $\gamma_\nu(\tau)\ \&\ \gamma_t(\tau)$, even though the traditional literature represents them as identical justified by the traditional derivation of the autocorrelation theorem. The derivation presented in Eq.12 that uses *integration over time* represents modeling the real physical process when the frequencies are physically present. The derivation in Eq.11 does not model any physical reality. The lesson is, as per the NIW-principle, that the time-frequency Fourier theorem (TF-FT) does not model reality for optical energy detection, which is a quadratic process, even though the detector stimulation is a linear superposition of all the stimulating fields, $\Psi = \sum_m \chi(\nu)E_m(\nu)$ (see Eq.1). However, the energy transfer to LCR oscillatory current by radio waves is proportional to the linear sum and hence the TF-FT models the physical process well [16,17] for radio waves.

While the mathematical Fourier transform of experimentally measured $\gamma_t(\tau)$ will generate the mathematical Fourier spectral density function $\tilde{A}(f)$, it does not represent any physical spectrum. The physical spectrum of the pulse $a(t)$ is determined by the source; it could contain a single frequency if we chop out a single pulse from a single mode CW laser; or it could contain multiple frequencies as in *frequency comb*, generated by modern fs pulsed lasers [18]. In fact, if NIW-principle were not correct, that is Fourier summation represented a real physical process and transformation of the summation of laser modes into a new single mean frequency, then only this mean frequency under a temporally oscillating envelope (Eq.13) would have achieved the gain and survived within the cavity and the *frequency comb* would have been lost!

$$E(\nu_0,t) = \sum_{-(N-1)/2}^{+(N-1)/2} e^{i2\pi(\nu_0+n\delta\nu)t+i\phi_c} = \frac{\sin N\pi\delta\nu t}{\sin \pi\delta\nu t} e^{i2\pi\nu_0 t+i\phi_c} \tag{14}$$

In other words, the NIW-principle tells us that the physical processes behind currently assumed laser pulse generation, or the traditional mode lock theory, are not tenable [4].

5. SPATIAL CORRELATION; SPACE-SPACE FOIURIER TRANSFORM (SS-FT)

Let us quickly build up the background before we get into the spatial correlation. The Huygens-Fresnel (HF) principle, represented by the HF-integral, is based on a physical model – waves propagate as if every point on the wave front generates a secondary spherical wave front, whose linear sum represents the complex amplitudes in any forward plane [12,19]

$$U(x) = \frac{-i}{\lambda} \iint_{\Sigma} U(\xi) \frac{\exp(ikr_{01})}{r_{01}} \cos\theta \; ds \tag{15}$$

The critical reader can immediately recognize a potential contradiction with our proposed NIW-principle. HF integral represents linear superposition of EM waves. And HF integral is the *master* equation in all branches of optical science and engineering wherever we need to propagate EM waves, whether for macro separation like star light coming to earth or for nano spacing of atoms as in nano photonics and plasmonic photonics. HF integral with support from Maxwell's wave equation, works! Further, Maxwell's wave equation accepts any linear sum of sinusoidal waves and arbitrary wave forms can be represented by a linear sum of a suitable set of Fourier monochromatic waves! Where is the validity of the NIW-principle? It is built into the HF integral! HF integral allows us to calculate the resultant complex amplitudes due to an aperture for any forward plane whatsoever. The clear implication is that all the secondary wavelets are allowed to propagate free of interaction (interference) with each other. HF integral is like a magic equation that allows us to propagate every single secondary wavelet independent of each other under the same integral. Note that the only way we can register the intensity of the diffraction pattern due to an aperture in any forward plane is by inserting a detector array, which carries out the quadratic interaction process and displays the energy distribution in that plane:

$$I(x) = \Psi^* \Psi = \left|\chi(\nu) U(x)\right|^2 = \left| \frac{-i\chi(\nu)}{\lambda} \iint_{\Sigma} U(\xi) \frac{\exp(ikr_{01})}{r_{01}} \cos\theta \; ds \right|^2 \tag{16}$$

It is because of the NIW-principle that HF integral works. So, the physical meaning behind the working HF integral and the Maxwell's wave equation is that the *space* that facilities the propagation of EM waves [20], can also support many many waves through the same physical volume as long as the sum total complex amplitudes keep the space into its linear state.

Since we have underscored earlier that we need to be careful while propagating Fourier frequencies due to a pulse, as they are non-physical, we mention here a generic case for propagating a short pulse through a diffracting, or imaging system. If we use a short pulse $U(P_1, t)$ in our optical system, then the HF integral for the complex amplitude response at a forward plane will be given by [19]:

$$U(P_0, t) = \frac{-i\nu}{c} \iint_{\Sigma} U(P_1, t) \frac{\exp(i2\pi\nu t)}{r_{01}} \cos\theta \; ds; \quad t = (r_{01} / c) \tag{17}$$

We want to briefly underscore here that replacing $U(P_1, t)$ inside the integral by its traditional Fourier integral, may or may not work depending upon the imaging/propagating system and the detection time constant. In fact, we have derived the most general formulation for a spectrometer illuminated with a generic pulse by directly propagating the pulse using only its carrier frequency, instead of CW Fourier monochromatic frequencies which evolves into various traditional formulations under special conditions of long time integration or when the pulse is longer than the spectrometer response time [21,22] and the concept has been extended to modeling a photon as a classical wave packet [23]. We have also experimentally demonstrated that simple modulation of a CW single frequency laser does not automatically give rise to Fourier frequencies that can be detected by heterodyne spectroscopy [21]. We now switch back to spatial diffraction so we can then explain the physical processes behind the degradation of fringe visibility due to an extended thermal ("incoherent") source.

We know that the HF diffraction integral of Eq. 15 morphs in the far-field into an integral resembling a spatial Fourier transform (Eq.18), because the secondary spherical wave fronts effectively behave as a set of plane waves for small angles [19]; where ξ & $f_x (= x / \lambda z)$ are the spatial Fourier conjugate variables representing the far-field phase variations as a linear product in the exponential factor. Thus, the space-space Fourier transform (SS-FT) integral of

Eq.18, extensively used for Fourier optics and optical signal processing, is firmly based upon the physical process in nature captured by the HF integral.

$$U(x) = \frac{e^{ikz} e^{i\frac{kx^2}{2z}}}{i\lambda z} \int_{-\infty}^{+\infty} U(\xi) e^{-i\frac{2\pi\xi x}{\lambda z}} d\xi = C \int_{-\infty}^{+\infty} U(\xi) e^{-i2\pi\xi f_x} d\xi; \;\; f_x = (x/\lambda z) \tag{18}$$

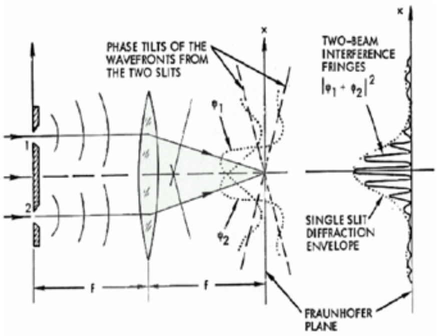


Figure 7. Fraunhofer diffrcation pattern due to two slits is the Fourier transform of the aperture function. The far-field is simulated by the traditional technique of using a convergent lens which converts the HF secondary wavelets into a set of convergent plane waves on the recording screen.

Let us now examine the van Cittert-Zernike theorem that gives the expression for the correlation function for EM waves between two spatially separate points at the far-field x-plane due to a thermal ("incoherent") source at the ξ-plane consiting of many independent emitters without any phase correlating mechnism between them. Consider Fig.8a and b. We want to find the correlation $\Gamma(x_1, x_2)$ between the fields at x_1 and x_2, which a detector will register where $\Gamma'(x_1, x_2)$ is the pure field-field correlation, not directly measurable:

$$\Gamma(x_1, x_2) \equiv \left\langle \chi U_x^*(x_1) \chi U_x(x_2) \right\rangle = \chi^2 \left\langle U_x^*(x_1) U_x(x_2) \right\rangle = \chi^2 \Gamma'(x_1, x_2) \tag{19}$$

It was recognized by Thompson [24, 12] that $\Gamma(x_1, x_2)$ can be measured as visibility of fringes using Young's double slit method. This experiemntal approach is very instructive because we can use this concept to demonstrate that the degradtion of spatial correlation between the two fields is equivalent to degradion of fringe visibility owing to spatial translation of two-beam fringes produced by each of the point source on the ξ-plane. The diffractively spreading photon wave packets from individual point sources do not become any more phase correlated than they were during the emission due to propagation with distance. But each of the individual expanding wave packets, having steady phase relation, cover wider and wider spatial areas as they propgate forward with distance. This spreading is at the root of observing enhanced fringe visibility (correlation) between spatially separate points. The experiemntal approaxch in ref.25 requires identifying any pair of points x_1 and x_2 and then insert an opaque screen with a pair slits at the desired locations. Then one records the fringes at the far field, α-plane and computes the fringe visibility. The far-field conditions are achieved by standard methos of choosing the ξ-, the x- and the α-plane at the front and back focal planes of a pair of convergent lenses as shown in Fig.8a&b. Then the time integrated (or ensemble averaged) detector signal $D(\alpha)$ at the α-plane due to a pair of slits at the x-plane would be given by:

$$\begin{aligned} D(\alpha) &= \left\langle \left| \chi U_\alpha(\alpha) \right|^2 \right\rangle = \left\langle \left| \chi U_x(x_1) + \chi U_x(x_2) \right|^2 \right\rangle \\ &= \left\langle \left| \chi U_x(x_1) \right|^2 \right\rangle + \left\langle \left| \chi U_x(x_2) \right|^2 \right\rangle + 2\,\mathrm{Re} \left\langle \chi U_x^*(x_1) \chi U_x(x_2) \right\rangle \\ &= D_1(\alpha) + D_2(\alpha) + 2 \left| \Gamma(x_1, x_2) \right| \cos\varphi_{12} \\ &= \left[1 + \beta\gamma_s(x_1, x_2) \cos\varphi_{12} \right] D_{1+2}; \;\; \beta \equiv \left[2\sqrt{D_1 D_2} \Big/ D_{1+2} \right]; \; \gamma_s \equiv (\Gamma / \sqrt{D_1 D_2}); \; D_{1+2} \equiv (D_1 + D_2) \end{aligned} \tag{20}$$

The last line of the above equation has been processed in such a way the $\beta\gamma_s$ represents the fringe visibility, which then helps one to extract the normalized γ_s, the desired field-field correlation expressed in Eq.19. Note that unequal amplitudes from the two slits $U_x(x_1)$ and $U_x(x_2)$ also reduce the fringe visibility through the factor β due to unequal detector signals $D_1(\alpha)$ & $D_2(\alpha)$. The reduction of visibility due to unequal amplitudes has nothing to do with the spatial phase correlation γ_s we want to measure to validate van Cittert-Zernike theorem. Of course, the best strategy is to pay attention to assure ahead of time that $D_1(\alpha)$ & $D_2(\alpha)$ are equal, then β reduces to unity.

Let us now derive the expression for the van Cittert-Zernike theorem to determine $\Gamma(x_1, x_2)$ defined in Eq.19. The expressions for $U_x(x_1)$ and $U_x(x_2)$ is easily determined by propagating a single HF wave let through the first lens on to the x-plane, which becomes a tilted plane wave crossing through the optical axis.

$$U_x(x_1) = \sum_m U_\xi(\xi_m) \exp[ik\xi_m x_1 / f]; \; U_x(x_2) = \sum_m U_\xi(\xi_m) \exp[ik\xi_m x_2 / f] \tag{21}$$

Substituting Eq.21 in Eq.19 and then by simplifying, we get the final expression Eq.22, which tells us that the degree of spatial phase correlation in the far-field is the Fourier transform of the intensity function [12]. The normalized spatial phase correlation function γ_s has been already defined in the last line of Eq.20.

$$\begin{aligned}\Gamma(x_1, x_2) &= \left\langle \chi U_x^*(x_1) \chi U_x(x_2) \right\rangle = \chi^2 \left\langle \left[\sum_m U_\xi(\xi_m) e^{ik\xi_m x_1/f}\right]^* \left[\sum_n U_\xi(\xi_n) e^{ik\xi_n x_2/f}\right] \right\rangle \\ &= \chi^2 \sum_{m=n} \left\langle U_\xi^*(\xi_m) U_\xi(\xi_m) \right\rangle e^{ik\xi_m(x_2-x_1)/f} + \chi^2 \sum_{m\neq n} \left\langle U_\xi^*(\xi_m) U_\xi(\xi_n) \right\rangle e^{ik(\xi_n x_2 - \xi_m x_1)/f} \\ &= \chi^2 \sum_{m=n} \left\langle U_\xi^*(\xi_m) U_\xi(\xi_m) \right\rangle e^{ik\xi_m(x_2-x_1)/f} + 0 \\ &\equiv \chi^2 \int_\xi I_\xi(\xi)\, e^{ik\xi_m(x_2-x_1)/f} d\xi \end{aligned} \tag{22}$$

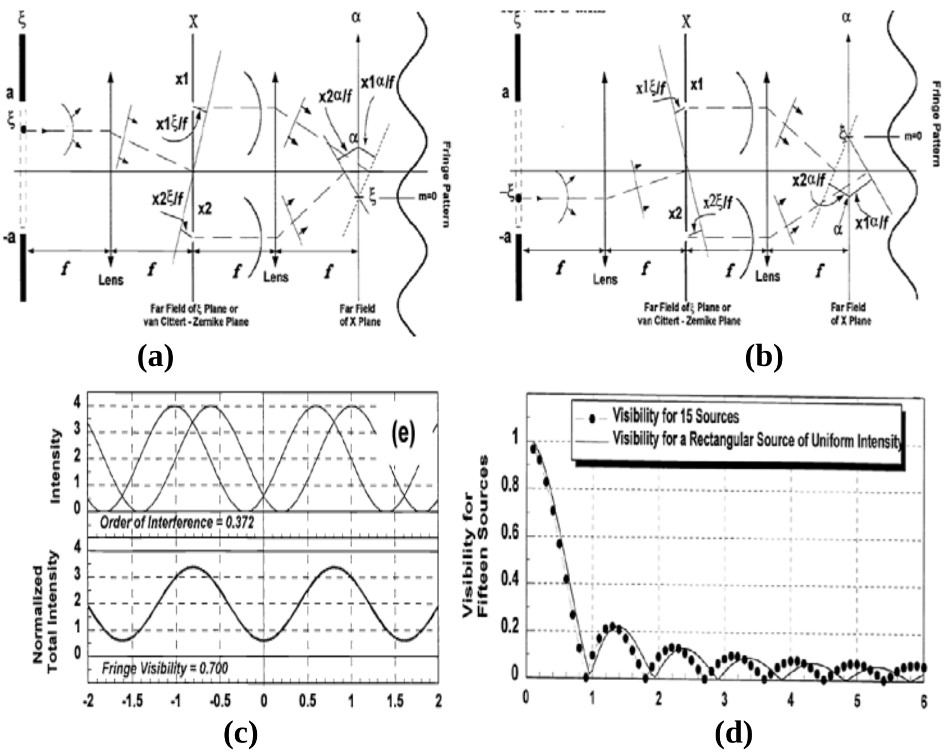


Figure 8. Far-field fringe visibility due to an incoherent source is the Fourier transform of the source intensity function, as per vn Cittert-Zernike theorem. Above diagrams help explain that the root of enhanced fringe visibility is due to the summation of many displaced, but perfect visibility fringes produced by each individual point source [25].

]Let us now try to appreciate the main point of this section that the degradation of the fringe visibility, assuming the correlating amplitudes are exactly equal, is due to the spatial translation of perfect visibility fringes corresponding to individual point source on the source plane [25]. Notice in Fig.8a&b we have chosen two spherically expanding source waves from $+\xi$ & $-\xi$ locations, above and below the optical axis. The consequent two sets of secondary pair of plane waves, generated by the pair of slits on the x-plane, arrive at the α -plane, intersecting each other below and above the optical axis, respectively. These two intersection points indicate the two optical image points corresponding to the source points located at $+\xi$ & $-\xi$ locations. This can be easily appreciated by recognizing that our optical system consists of a double spatial Fourier transform arrangement. The α -plane is an inverted image of the ξ-plane. In any perfect optical imaging system, the relative path difference between all possible rays starting from an object point and arriving at the corresponding image point is zero. Thus, the order of interference for the fringe peak shown on the α -plane below the optical axis of Fig.8a, produced due to the source point $+\xi$, is zero, or $m = \nu\tau = \nu.(\Delta / c) = \Delta / \lambda = 0$. Similarly, the zero order fringe peak due to the source point $-\xi$ is shifted above the optical axis. This lateral spatial displacements of otherwise perfectly visible fringes due to each source point, reduces the effective fringe visibility, given by the vC-Z theorem. Phase correlation between different source points remain unaltered through diffrcative spreading of the individual source waves. They do not interact to modify each other in the absence of some interacting medium. The logical argument is built into the NIW-principle.

Fig.8c shows this visibility reduction due to one pair of source points. When one continues to sum displaced fringes due to more and more points on the source plane and plots them for a given pair of slits on the x-plane, one can approach the analytical curve given by the vC-Z theorem, as shown in Fig.8d.

6. COMPLEX CORRELATION

In the last three sections we have given simple derivations to justify why correlation functions should be explicitly indentified with the specific physical parameters of the waves being analyzed, like frequency, time varying amplitude and space varying random phase. But each of the parameters was considered separately. In real life, light in many practical cases may have several variable parameters present simultaneously. Then extracting the precise values for correlation factor and the relevant physical parameters from the recorded fringe visibility or the correlation factor becomes very difficult. In this section, we treat a slightly complex case where we have a single pulse (time varying amplitude) which contains multiple frequencies, like the comb-frequencies in single pulse clipped off from a mode lock laser. For mathematical convenience, we assume that the mode locked laser had an intra-cavity gain equalizing device so the frequency comb consists of equal amplitudes. Then the time integrated detector output due to a pair of replicated and delayed pulses would be given by:

$$\begin{aligned} D(\tau) &= \int I(t,\tau)\, dt = \int \left| \sum_{-(N-1)/2}^{+(N-1)/2} d(t) e^{i2\pi(\nu_0 + n\delta\nu)t} + \sum_{-(N-1)/2}^{+(N-1)/2} d(t-\tau) e^{i2\pi(\nu_0 + m\delta\nu)(t-\tau)} \right|^2 dt \\ &= \sum_{-(N-1)/2}^{+(N-1)/2} \int_{-\infty}^{+\infty} \left| d(t) e^{i2\pi n\delta\nu t} + d(t-\tau) e^{i2\pi n\delta\nu(t-\tau)} \right|^2 dt \\ &= \sum_{-(N-1)/2}^{+(N-1)/2} \left[2E + 2\cos 2\pi n\delta\nu\tau \int_{-\infty}^{+\infty} d^*(t) d(t-\tau) dt \right] \\ &= 2E \sum_{-(N-1)/2}^{+(N-1)/2} \left[1 + \gamma_t(\tau) \cos 2\pi n\delta\nu\tau \right] \\ &= 2E \left[N + \gamma_t(\tau) \sum_{-(N-1)/2}^{+(N-1)/2} \cos 2\pi n\delta\nu\tau \right] \\ &= 2E \left[N + \gamma_t(\tau)\gamma_\nu(\tau) \right] \end{aligned} \tag{23}$$

The measured fringe visibility is now a product of temporal and spectral correlations, defined and developed in the previous sections.

7. SUMMARY

We have identified and applied the NIW-principle (Non-Interaction of Waves) to develop a deeper understanding of the physics behind degradation of fringe visibility that provides the experimental foundation behind various optical correlation functions. Since direct field-field correlation is not measurable as they do not interact, we have focused on the physical light-matter interaction processes, which we have defined as the Interaction Process Mapping Epistemology (IPM-E).Then, based on these NIW-principle and the IPM-E, we have derived and re-defined the measurable correlation functions that directly identify the physical parameters of the light waves being analyzed. Accordingly, there are four distinctly different identifiable optical correlation functions: (i) Spectral visibility or correlation (multi frequency light). (ii)Temporal visibility or correlation (pulsed light). (iii) Spatial visibility or correlation (independent multiple emitters). And (iv) Complex visibility or correlation (mixture of the above cases).

The two key lessons that we have learned are as follows. (i) There are no field-field correlations (or interactions) between EM waves (the NIW-principle). Detectors determine what we observe (measure). Hence, we must be extremely cautious that we do not impose the quantum properties of detecting materials on to the EM waves. (ii) The response and integration times of detectors and their associated circuits determine the registered visibility of fringes (correlation). If we can invent an atto second detector and a complementing time resolved register (much faster streak camera), then all light sources will provide high visibility fringes. So, we should not assign characteristics to light like *incoherent* or *partially coherent* without referring to the measurement (detectors') time constants. Light is never *incoherent*! Our detectors are slow compared to the optical frequencies!

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