ON THE PHASE CHARACTERISTICS AND COMPRESSION OF PICOSECOND PULSES

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It is pointed out that published data on the compression of mode-locked Neodymium-glass pulses do not require the pulse to have a predominantly positive frequency sweep. It is s random pulse carrier phase function, for example, can account for published experiment tions.

Recent experiments[1,2] on mode-locked Neodymium-glass laser pulses have led to the detection of a quadratic term in the pulse carrier phase $\varphi(t)$, i.e., $\varphi(t) = -\omega_0 t - \frac{1}{2}\beta t^2$ (corresponding to a

linear sweep of the carrier frequ
reported was the resultant comp
pulses when passed through a di
line on account of β being positi
could be regarded as evidenc
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train of picosecond pulse

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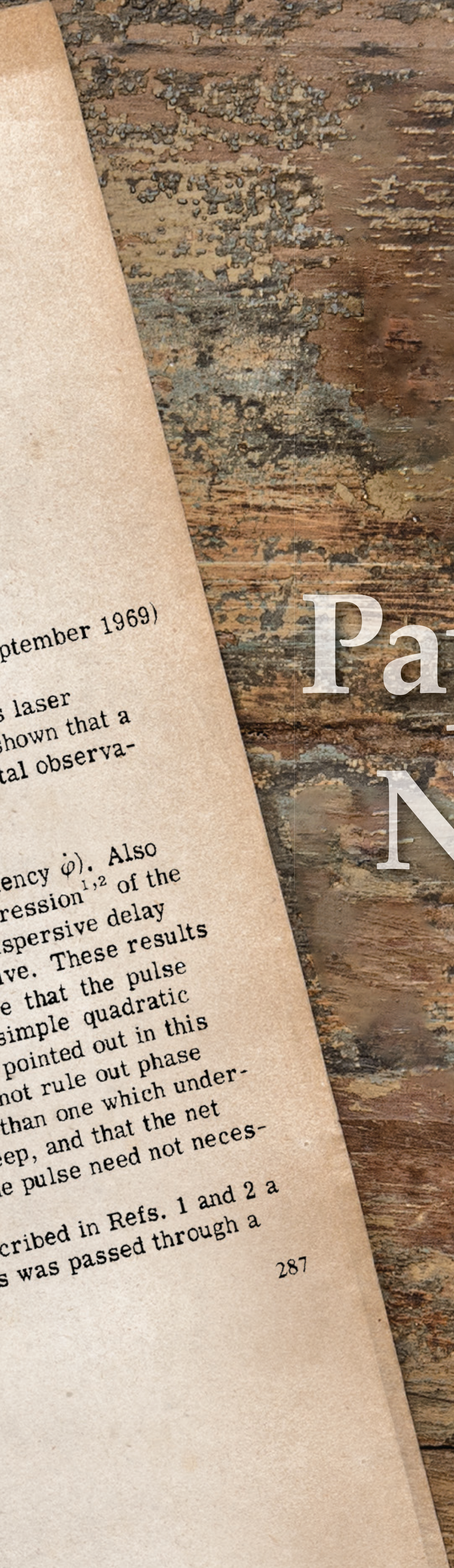
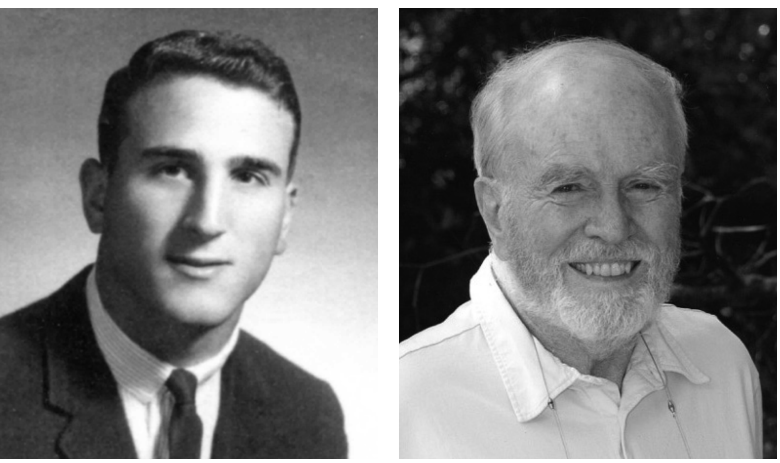
The Most Important Paper You've Never Read

A half-century ago, a seminal but largely forgotten study identified the "coherent artifact" in measurements of ultrashort laser pulses.



Editor's note: Just over 50 years ago, in November 1969, a paper in Applied Physics Letters *by Robert A. Fisher and Joseph A. Fleck Jr. identified a problem in the measurements of the sub-nanosecond laser pulses that were starting to come on the scene. In this essay, to mark the golden anniversary of that paper's publication, OSA Fellow Rick Trebino of the Georgia Institute of Technology, USA, offers a personal recollection of his encounter with this seminal paper—and its lead author.*



Bob Fisher (left) at about the time of the publication of the classic paper, and Joe Fleck a decade or two later.
Courtesy of Bob Fisher / Courtesy of the Fleck family

It was the 1960s. I was in grade school, and many of you weren't even born yet. But a new breed of scientist—the laser scientist—had just emerged and was creating the narrowest-band light sources ever seen. The light was spectacularly beautiful—and, more important, spectacularly useful.

Not to detract from the brilliance and accomplishments of those early workers, but lasers naturally tend to narrowband emission, their spectra narrowing further on every pass through the gain medium. So, as scientists always love a challenge, a small subset of these pioneers elected to attempt the opposite—the development of broadband lasers—despite the obvious challenges. There was good reason to do so. By the uncertainty principle, narrowband laser pulses are naturally long in duration and hence low in peak power. But, if researchers could develop broadband lasers, those devices could potentially generate very short pulses with very high peak powers.

Unfortunately, it takes much more than a broad spectrum to create a short pulse—an incandescent lightbulb is also quite broadband, and it's about as far from a short pulse as you can get. So, in addition, all the frequencies present also had to line up in phase at one time, and out of phase at all other times—that is, all the frequency modes had to be locked in phase. This was where genius was required, and this new community proved worthy of the task, proposing and demonstrating numerous clever "mode-locking" approaches, some of which worked better than others.

The measurement challenge

But there was another challenge. As OSA Fellow Wayne Knox famously said, "If you haven't measured it, you haven't made it." By the late 1960s, laser pulses had broken the nanosecond barrier and achieved picosecond durations—shorter than could be measured using available measurement techniques such as photodiodes and oscilloscopes. These ultrashort pulses required a new measurement technique.

The problem was that, to measure a short event in time, you need an even shorter one. Time-resolving a bubble popping, for example, requires a strobe-light pulse shorter than the time it takes for the bubble to pop. Unfortunately (or fortunately, depending on how you looked at it), these newly created laser pulses had become the shortest events ever generated; by definition, no shorter event was available. The best that researchers could do was to use the shortest event they had—the ultrashort pulse—to measure itself.

The resulting technique, invented in 1966, was called intensity autocorrelation. All it required was a fast nonlinear-optical effect. More specifically, splitting the pulse in two, overlapping both resulting pulses in the nonlinear medium, and varying the delay between them did the trick. If the pulses overlapped in time, nonlinear-optical signal light was generated. If not, then no such light was generated, leaving only light from the individual pulses. Simply plotting the nonlinear-optical signal light energy versus time yielded an image of the pulse. It was a blurry black-and-white one, but it provided an approximate pulse length (within around 20%), which was good enough.

Intensity autocorrelation quickly became the standard of ultrashort-pulse measurement. It was easy to

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It was the annoying "background," and not the more impressive, narrow spike atop it, that indicated the true pulse length. The narrow spike came to be known as the coherent artifact.

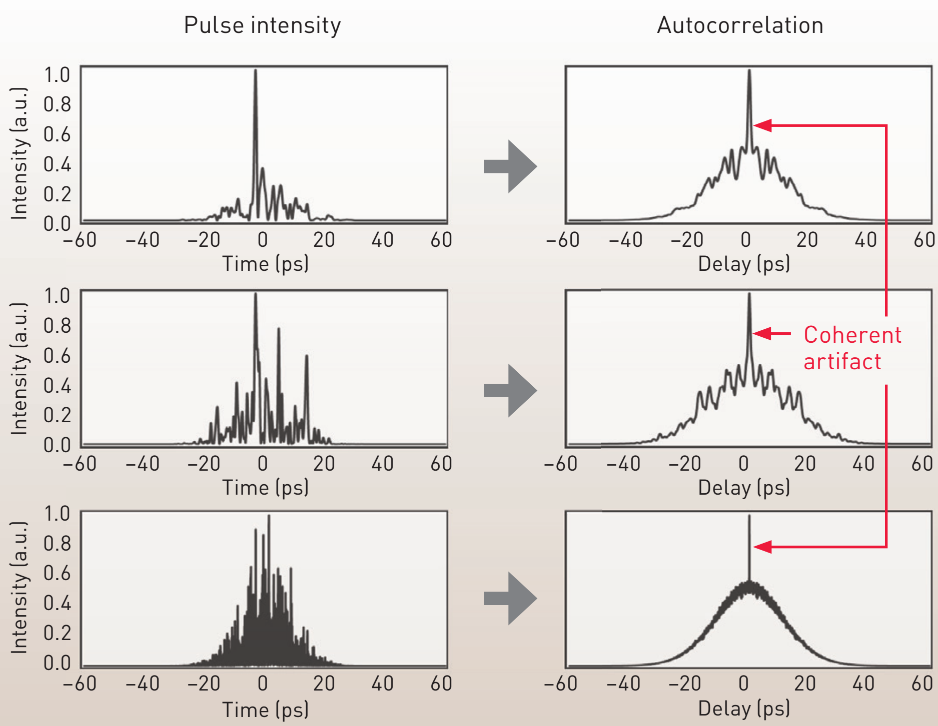
compute autocorrelation curves for various simple pulse shapes. So, by assuming a pulse shape, one could simply divide a pulse's autocorrelation width by a number associated with that pulse shape and, if the assumed pulse shape was correct, obtain the actual pulse duration. Autocorrelation allowed issues in the lasers that lengthened pulses to be identified and corrected, and pulses became even shorter.

Autocorrelation's hidden hazard: The coherent artifact

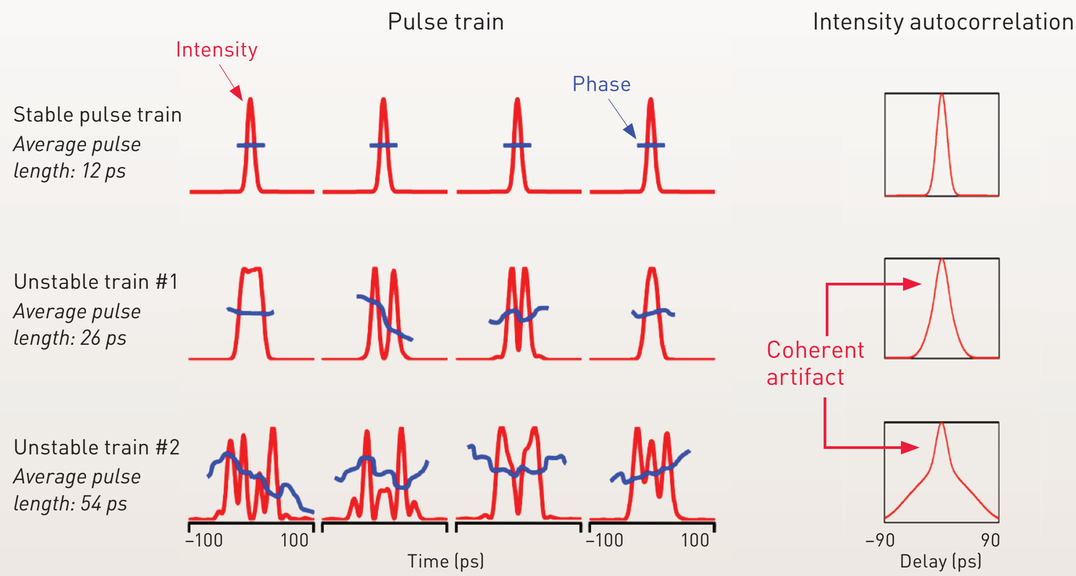
Occasionally, however, the autocorrelation trace's expected narrow peak sat atop a much longer background. Many who saw this attributed the long background to artifacts such as stray light finding its way into the detector or some other benign, irrelevant effect. In this emerging new field, of course, everyone wanted to claim the shortest pulse, so it was easy to overlook this seemingly minor, pesky effect.

Unfortunately, as that initial decade wound down, it was discovered that this annoying "background," and not the more impressive, narrow spike atop it, in fact indicated the true pulse length. The narrow spike instead actually indicated the shortest temporal structure within the pulse. It came to be known as the coherent artifact.

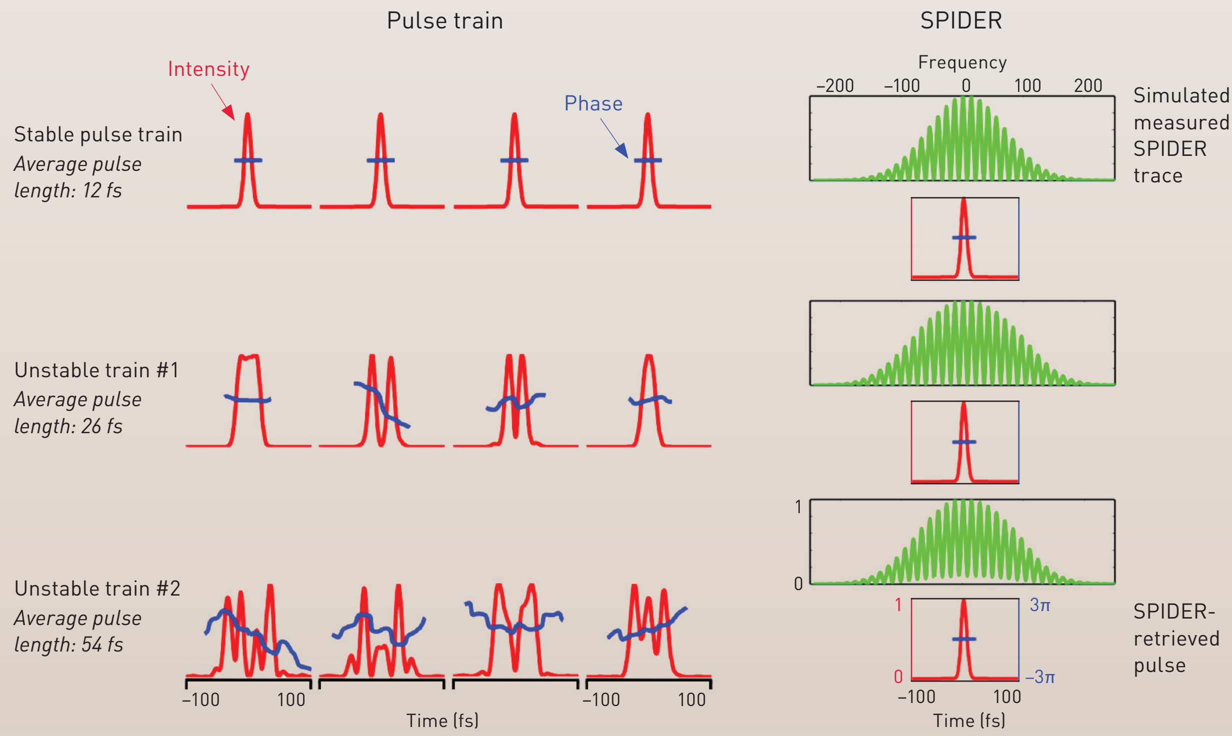
Confusing the coherent artifact for the actual pulse was an easy mistake to make. The odd two-component curve (broad background and narrow spike) was quite unintuitive because it resulted from cancellations occurring in the addition of always-positive intensities. It occurred because complex



As pulse intensity versus time becomes more complex, its autocorrelation approaches a broad background plus a narrow spike—called the coherent artifact—that can be much shorter than the actual pulse. www.frog.gatech.edu



These simulations show that autocorrelation of a stable, simple pulse train (top row) yields a correct result. But autocorrelations of unstable, moderately complex pulse trains (middle and bottom rows), each comprising a 12-ps stable component plus a longer unstable one, form a coherent artifact unrelated to the actual pulse width and shape. Unstable, moderately complex pulse trains in particular (middle row) still yield simple autocorrelations in which it can be difficult to distinguish the coherent artifact from the background. Here, a common sech^2 pulse shape fits the middle row's autocorrelation well, but significantly underestimates the pulse duration.



Recent research and numerical simulations show that some modern interferometric pulse-measurement techniques, when confronted with complicated pulse trains, measure only the coherent artifact. The spectral-phase interferometry for direct electric-field reconstruction (SPIDER) technique, for example, retrieves nonrandom pulse trains perfectly, but returns only the shorter, nonrandom component of the pulse train—the coherent artifact—for random, longer-pulse trains. Techniques with these characteristics cannot distinguish a stable train of short simple pulses from an unstable train of long, complex pulses.

Adapted from J. Ratner et al., Opt. Lett. **14**, 2874 (2012).

Time passed, and as ultrashort laser pulses became shorter, simpler, and more stable—that is, better—many forgot about the coherent artifact.

pulses effectively have intensity oscillations in time. When the delay between the two pulses is zero, they overlap perfectly and their product's integral is maximal; imperfect overlap yields an integral with contributions from products of high and low intensities, which is always less. The effect was particularly problematic when the measurement averaged over many different pulse shapes.

All this wasn't so obvious at the time, however, and those who misinterpreted the curves could easily be forgiven for their mistake.

Obscure origins

Entering photonics more than a decade later, I became fascinated by ultrashort pulses and their measurement—and, especially, by the coherent artifact and its underlying psychology. The numerous articles and books I read on ultrashort pulses all mentioned the infamous coherent artifact. Its misinterpretation in the 1960s was a perfect example of the self-deception and wishful thinking that humans are particularly susceptible to. Notorious examples of this phenomenon abound. They include spurious scientific "discoveries" such as the "N-rays" described by the French physicist Prosper-René Blondlot in 1903 and subsequently debunked; the embarrassing Piltdown Man hoax, which survived for almost the entire first half of the 20th century; and the spectacular short life of the late-1980s claims of cold fusion.

At the time, I wondered who had first identified and described the elusive coherent artifact. None of the books or papers I read, however, mentioned those responsible for this important realization and for its clear and careful delineation. This was, perhaps, understandable—scientists don't like making mistakes any more than anyone else. Glory tends to be reserved only for those who make new discoveries, not those who debunk old ones.

A lesson forgotten

Time passed, and as ultrashort laser pulses became shorter, simpler, and more stable—that is, better—many forgot about the coherent artifact. Students no longer were taught it, and many young ultrafast-laser scientists today have never even heard of the term. I went on to take a research position at a national lab and then another as a professor. In the back of my mind, though, I continued to wonder who had first identified the coherent artifact.

My interest intensified considerably in the 1990s when I, along with several talented postdocs, developed a technique for completely measuring ultrashort laser pulses, yielding not a blurry black-and-white image but a high-resolution, full-color image of the pulse—in other words, the complete temporal intensity and phase. I called it frequency-resolved optical gating, yielding the light-hearted acronym, FROG.

We quickly determined that FROG did not suffer from coherent-artifact problems and, even better, could actually indicate the stability or instability of a pulse train. Within a decade, a host of other full-color pulse-measurement methods had also emerged. Many of these methods, which became quite popular, often yielded pulses considerably shorter than when measured by FROG.

Ultrashort-pulse measurement is actually more difficult than many realize because not all modern ultrashort-pulse lasers are inherently stable. In particular, lasers operating at the edge of technology are the least likely to have stable pulse shapes. They're also the most in need of measurement. So a team including myself, grad student Michelle Rhodes, and Günter Steinmeyer decided to consider the new methods of pulse measurement, and what they yielded when presented with a train of pulses with unknown, unstable and potentially complex pulse shapes.

We were surprised to find that, for some of the methods, the coherent artifact was the *only* thing that was being measured. Other methods yielded a hint of the pulse shape instability, but usually not much of one. For standard, high-rep-rate, relatively long (~100 fs) pulses, these measurement techniques

Although Joe Fleck Jr. passed on a few years ago and Brian Treacy also did so very recently, Bob Fisher remains physically and scientifically active and currently manages the CLEO short-course program.
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could yield correct results. However, for the shortest pulses, where instability was more likely an issue, the same self-deception that had occurred previously re-emerged. To paraphrase Santayana, those who forgot about this inconvenient piece of history were condemned to repeat it.

Scientific archaeology

As we sat down to write the first paper on this work, we realized that we needed to cite the paper that had first elucidated the coherent artifact more than four decades earlier. And, unfortunately, we simply couldn't find it. Such an old publication can be notoriously difficult to find, especially when one doesn't know who wrote it. So, I decided that, the next time I was at a scientific conference, I would ask everyone older than myself if they knew anything about it. It promised to be a difficult task—so much time had passed, the terminology had changed so much, and so few researchers from that era remained in the field.

The first person I encountered at the conference Sunday evening reception was a well-known scientist, and someone that I'd personally known for years, Bob Fisher, who seemed about my age, not older. Nevertheless, I asked Bob if he knew who had made this important but evidently thankless breakthrough. He responded, "It was me!" Surprised, I told him how hard I'd searched without success for this seemingly ancient paper. He answered, with a smile, "That's probably because I wrote it in cuneiform on cheap papyrus."

I had, it turns out, been engaging in a form of scientific archaeology—and, thanks to my chance encounter with Bob, had dug in the right place on my first try, and excavated an "ancient," monumental contribution from the sands of scientific obscurity. In close to 50 years since its publication, the classic paper coauthored by Bob that had first exposed the coherent artifact, correcting an entire new field's misconceptions, had been cited only seven times.

This explained why so many researchers and laser companies still use methods, including intensity autocorrelation, that measure, in many cases, only this misleading quantity. Indeed, numerous individuals have told me that they or their company needed to continue to use one of these new methods to obtain pulse durations competitive with others that use the same techniques.

A courageous step

It was fascinating to learn of Bob's experiences publishing such a historic paper—a paper that invalidated others' erroneous claims and wreaked such (necessary) havoc in the field at the time, but potentially saved much future embarrassment. In looking back, it's clear that it took a great deal of courage to do so.

At the time, Bob was a young graduate student in physics at the University of California, Berkeley, USA, with two years to go before graduating. He had read of the latest picosecond-pulse measurements by Brian Treacy, a man Bob considered a hero of the field and whose accomplishments remain legendary even today. But in 1969, Treacy's latest results made no sense: An autocorrelation trace of an uncompressed (that is, long) pulse was narrower than a cross-correlation of it with a compressed, shorter pulse.

"This kept me up for nights," Bob told me. "Finally, I asked myself the irreverent question, 'Could my great hero have failed to properly interpret his data?' I started to wonder if a randomly modulated [that

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is, complex] pulse could actually be a better fit with his data."

So, Bob performed the relevant simulations and discovered that long complex pulses could yield a narrow central spike, which explained the results. To be absolutely sure, he asked a well-respected scientist from the Lawrence Livermore National Laboratory, Joseph Fleck Jr., to confirm his results and coauthor the resulting paper—a paper that would tell older, much more established scientists that their measurements were wrong.

"Because of my great respect for Brian," Bob continued, "I chose a title that was not negative: 'On the phase characteristics and compression of picosecond pulses.' The paper was designed to point out the error only to those who read it carefully." He added, "I wanted to conclude the paper with the statement that autocorrelation measurements are very much like a 'fairy godmother,' in that they give you what you're hoping for. Although Joe and I decided in the summer of 1969 not to end with the 'fairy godmother' comment, in retrospect I am sorry that we didn't. I still believe that autocorrelation measurements possess fairy-godmother qualities."

I can confirm that this somewhat frivolous statement is actually not too far off. In our work, we've found that, when the central spike is only a factor of two or three shorter than the background, it blends in with the background and gives the appearance of a shorter pulse in the absence of a coherent artifact.

Crediting the accomplishment

The good news is that, back in 1969, Bob's hero, Brian Treacy, took the news well—a testament to his scientific wisdom and maturity. Indeed, soon afterward, Treacy himself developed a vastly improved pulse-measurement method (a bit like FROG), which unfortunately was quickly forgotten and only rediscovered decades later.

Not everyone reacted so positively, however. Bob told me that at least one researcher whose measurements his paper debunked never spoke to Joe or him again. And while we can only speculate, the almost complete lack of citations to the Fisher and Fleck paper may well reflect a lack of enthusiasm for it by many others so affected by its results.

Our hope is that, in recognizing the accomplishments of Fisher and Fleck on the occasion of the paper's 50th anniversary, we're helping to give credit where credit is due. And, perhaps, we'll not repeat the mistake of forgetting this particular past once again. OPN

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