Conceptual illustration of atmospheric turbulence.

A. Efetova / Getty Images

How USAF Funding Shaped Laser–Atmosphere Modeling

A transformative software for nonlinear laser–atmosphere interactions illustrates how long-term basic research investment drives scientific and technological impact.

Connemara Doran and Arje Nachman

For over a decade, US federal research laboratories have funded and carried out research on ultrashort pulse lasers (USPLs). This article explains how two decades of targeted, sustained funding by the Department of the Air Force's basic science funding arm (the Air Force Office of Scientific Research, or AFOSR) led to the development of a breakthrough software package that enables precision nonlinear modeling of laser–atmosphere interactions.

Through historical and bibliometric analysis, we show that this technique has become a gold standard in the fields of high-intensity laser physics and optics. Nurturing of this breakthrough across different valleys of death over two decades by AFOSR and the funded principal investigators has had a transformational impact on laser physics and on applications in directed energy.

Since the early years of laser physics in the 1960s, scientists have grappled with the complexities of light–matter interactions that arise when high-intensity beams propagate through different types of media. Multiple Nobel Prizes in Physics have been awarded to researchers addressing these questions, from AFOSR-funded Charles Townes in 1964 to AFOSR-funded Pierre Agostini and Ferenc Krausz (with Anne L'Huillier) in 2023.

When intense laser beams travel through certain materials (such as crystals or gases), the polarization density of the media responds nonlinearly to the electric field of the light. An entire discipline—the field of theoretical and experimental nonlinear optics—grew out of the question of how to analyze the nonlinear response of a medium to high-intensity light.

One particularly important nonlinear medium is the Earth's atmosphere. In the 1990s, interest grew in how laser beams might interact with molecules such as nitrogen, oxygen and water. Experimental studies in the mid-1990s revealed novel observations that needed theoretical explanation. In 1994, a team at the University of Michigan, USA, led by Gérard Mourou observed filament propagation of chirped-pulse-amplified terawatt laser pulses in the atmosphere. (Mourou would go on to win the 2018 Nobel Prize in Physics with his former student Donna Strickland for their work on chirped-pulse amplification to produce high-intensity ultra-short optical laser pulses).

1047-6938/26/04/42/6-$15.00 ©Optica

The Earth's atmosphere is an important nonlinear medium. In the 1990s, interest grew in how laser beams might interact with molecules such as nitrogen, oxygen and water.

M. Colombo / Getty Images

In these experiments, the laser's electric field changes the refractive index of the propagating medium via the Kerr effect, which leads the beam to self-focus. The self-focusing refraction is balanced by the self-attenuating diffraction due to ionization and rarefaction of the beam, producing plasma "filaments" that act as waveguides for the laser. Mourou's team used laser pulses with a peak power of 10 terawatts (ten trillion watts, corresponding to a flow of energy of ten trillion joules per second) lasting only 100 femtoseconds (or 10^{-13} seconds). The peak energy inside these ultra-short pulses is high enough to ionize air, turning it into plasma in a process called filamentation.

A plasma waveguide can optically guide an ultra-intense laser pulse over long distances. Filaments (narrowed, self-focused electromagnetic pulses) act as their own waveguides, retaining their width and propagating for tens of meters or more. Filamentation could be an effective tool in directed-energy applications, providing the ability to affect matter in a consistent way without needing to know the precise location of a target.

After the experimental demonstration of filamentation, there was not yet a coherent model to describe and explain the process. In the mid-1990s, the physicist Jerry Moloney at the Arizona Center for Mathematical Sciences (ACMS) and the AFOSR Program Officer Arje Nachman discussed the possibility of producing such a model to mathematically describe how short laser pulses interact with the atmosphere. Nachman subsequently started funding theorists, including Moloney's team at the ACMS, to identify what fundamental equations of physics can reveal about the behavior of laser pulses in the nonlinear environment of the atmosphere.

Building an interdisciplinary hub for nonlinear optics theory

The ACMS grew as an interdisciplinary program within the department of mathematics at the University of Arizona in Tucson, AZ, closely tied to the College of Optical Sciences. In 1979, Physics Nobel laureate Willis Lamb was looking for a theorist to join the Optical Sciences Center and hired Jerry Moloney, an expert in the applied mathematics, theory and experimentation of electromagnetic waves.

When Nachman arrived at AFOSR in 1985 to manage the physical mathematics portfolio, he wanted to fund research in nonlinear partial differential equations as part of his vision that strong theoretical foundations are essential for experimental advances, a conviction he later carried into his electromagnetism portfolio. In contrast to many portfolios that emphasize experiments, Nachman chose to fund theory only and actively sought out researchers in mathematical and theoretical nonlinear optics.

Alan Newall, a leading applied mathematician whose work spanned optics, water waves and other media and who had extensively studied the nonlinear Shrödinger (NLS) equation, became chair of the mathematics department at the University of Arizona. He introduced Nachman to Moloney. In 1986, Moloney joined ACMS, and four years later he became a chaired professor of optics and mathematical sciences. In 1998, he recruited Miroslav Kolesik to the ACMS to work on the mathematics of nonlinear optics.

Both Moloney and Kolesik had interdisciplinary training in their undergraduate and graduate work that enabled them to apply mathematical insight to problems within physics and optics: Moloney had been trained in physical chemistry, mathematics and physics; Kolesik in nonlinear optics, mathematics, and statistical and computational physics.

From the NLS equation to UPPE

Over several decades, AFOSR funding of the ACMS led to many breakthroughs in theoretical and experimental nonlinear optics. Between 1998 and 1999, the ACMS team published two key papers that set the groundwork for

> Filamentation could be an effective tool in directed-energy applications, providing the ability to affect matter in a consistent way without needing to know the precise location of a target.

explaining filamentation and modeling high-intensity pulses in nonlinear materials.

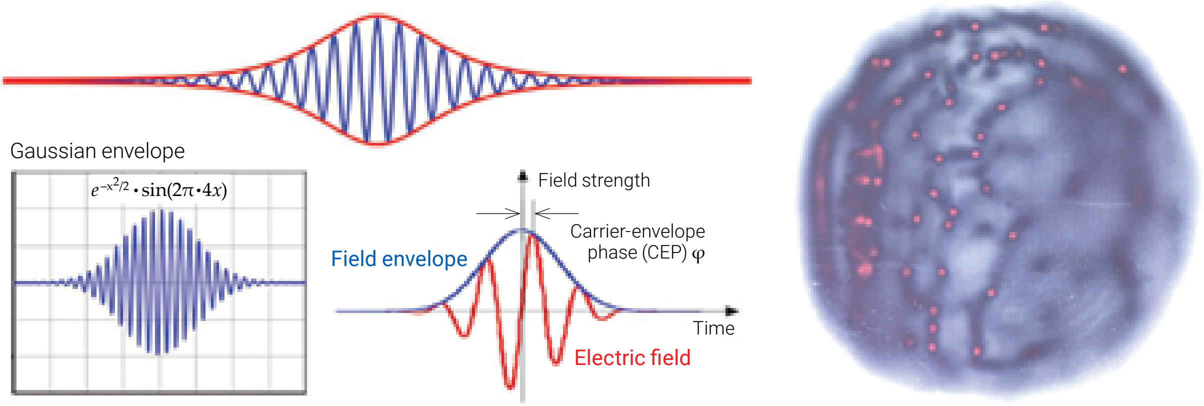
The theoretical basis of these results was the three-dimensional non-linear NLS equation: in the figure below, the “envelope” surrounding the varying amplitude of the optical carrier wave is the solution to the NLS equation. In their 1998 *Optics Letters* paper, Moloney, Kolesik, Mlejnek and Wright “established the mechanism for describing the evolution of an isolated laser filament: called dynamical spatial replenishment, this identified the filament initiation via Kerr self-focusing followed by plasma defocusing.”

One year later, a *Physical Review Letters* paper by Moloney, Kolesik, Mlejnek and Wright “introduced the notion of random high power multiple filamentation (optical turbulence),” making the key observation that filaments appear and disappear in bursts and are sustained by a background “energy reservoir.” Both phenomena—dynamical spatial replenishment and multiple filamentation sustained by an energy reservoir—were experimentally verified in 2003 by a Franco-German collaboration supported by the Teramobile project. Courvoisier and colleagues in the Franco-German team introduced the term “photon bath” for what the ACMS team had called “energy reservoir.”

However, the NLS equation had limited effectiveness for modeling ever-shorter pulses in nonlinear environments. This limitation of the NLS model led to the development of a far more effective model: the unidirectional pulse propagation equation (UPPE), which was developed by the ACMS team with AFOSR funding between 2001 and 2004.

UPPE is a numerical translation of the nonlinear Maxwell equations governing pulse propagation. It is “unidirectional” because lasers do not experience significant back-scattering in air. The original UPPE formulation was a general vectorial equation based directly on the Maxwell equations, later implemented in a simpler scalar form for practical use.

In their 2002 *Physical Review Letters* paper introducing UPPE, Kolesik, Moloney and Mlejnek noted that although the NLS equation is “a remarkably robust description of weakly nonlinear dispersive wave propagation” and can be derived from an asymptotic expansion in a small parameter of Maxwell’s equations in optics, the advance of “extreme femtosecond nonlinear optics” has led to situations where the validity of the NLS model, even with correction terms included, comes into question. As Moloney observes, the NLS equation is “natural” to adapt, since it “describes weakly nonlinear dispersive behavior in any physical system—optical propagation, water waves, or plasma instabilities in Langmuir turbulence.” However, just as self-focusing moves toward a singularity, NLS solutions



Left: Nonlinear envelope approximation model. Right: Image of multiple filamentation of intense laser pulse in air from experiment carried out by the Naval Research Laboratory, Plasma Physics Division, USA.

J. Moloney, “Long Range Femtosecond Atmospheric Mid-IR Light Bullet” lecture on research supported by AFOSR MURI Grant # FA9550-10-1-0561

The development of UPPE has fundamentally transformed our understanding of how ultrafast, intense laser pulses interact with nonlinear media.

themselves become singular unless processes such as multiphoton ionization, which strips electrons from atoms and creates plasma, are included.

Rather than relying on slowly varying NLS envelope approximations, the ACMS team (with Miroslav Kolesik playing a central role) derived UPPE, providing a transition from Maxwell's equations to the approximate envelope-based models. While NLS envelope models approximate the polarization term in the full vector Maxwell simulations of short pulses in nonlinear media, the UPPE gives the polarization term exactly (it is not an approximation). The team proposed two varieties of the UPPE: time- and space-dependent versions.

A follow-up article in *Physical Review E* in 2004 by Kolesik and Moloney (by then Mlejnek had moved to Corning's optics research lab) expanded the formulation and applications of UPPE. They derived spatial- and time-domain versions of UPPE and compared them "from the point of view of their practical application in simulations of nonlinear optical pulse dynamics."

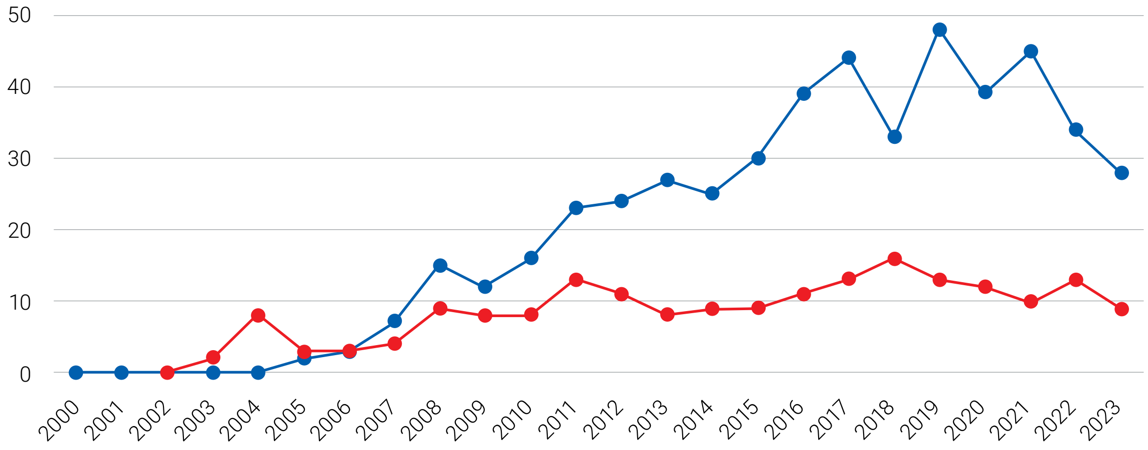
In 2023, they wrote that the spatial-domain version of UPPE has "survived for many decades and has become the computational workhorse for researchers studying filamentation in gases and solids, high-harmonic generation and THz generation in gases and solids, and interactions of intense ultrashort pulses with plasmas." UPPE is realized as both an algorithm and a software package available for free download to researchers in short-pulse laser physics at universities and government laboratories. It is research code designed for expert users rather than a commercial product.

From a mathematical perspective, Kolesik and Moloney explain, UPPE "provides a robust full field canonical description" from which envelope models such as the NLS equation in which "dispersion dominates over nonlinearity," or full field equations "where nonlinearity dominates dispersion," can be asymptotically derived as limiting cases.

From an experimental or observational perspective, they say UPPE surpasses other established propagation models in its ability to capture "complex atmospheric spectral interaction" windows without the "huge computational challenges" other models would face.

Growth in citations of foundational UPPE papers

An examination of historical citation data shows a strong and sustained growth in citations to the two foundational papers establishing the UPPE technique, from their publication in 2002 and 2004 through 2023. Both works exhibit consistently high citation rates over nearly two decades, a behavior that is very unusual. The typical citation trajectory rises to a peak followed by a steady decline. By contrast, if a paper is truly



Citations of the 2002 and 2004 UPPE articles, 2003–2023.

Source: Dimensions

foundational for a field, describing a new technique that the community of practitioners recognizes and adopts, then its citation curve would maintain long-term momentum. The analysis of historical citation data observed in this case strongly suggests that these two papers are widely considered foundational contributions defining an authentically new technique in nonlinear optics: UPPE.

Overall, the citation record confirms both the longevity and breadth of UPPE's impact within the nonlinear optics community, with many citations compared with the total number of papers published within this subdiscipline of optics and laser physics.

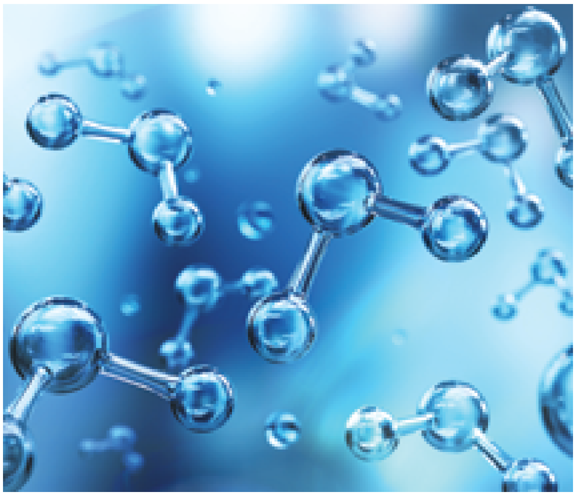
How short-pulse lasers interact with atmospheric molecules and other UPPE applications

After developing UPPE, Kolesik turned to a key question: How can we model and predict the way that short-pulse lasers interact with atmospheric molecules such as nitrogen, oxygen and argon? In essence, what is the mathematical description of what happens when an ultrashort pulse strikes the most common molecules in air?

Kolesik incorporated the answers he found in this modeling into later versions of the UPPE algorithm. Moloney, meanwhile, also published an article on the interactions between ultrashort pulses and water molecules. The research showed that long-wave infrared ultrashort pulses can shatter water droplets and potentially be used to locally clear fog or clouds in the atmosphere while avoiding "undesirable electron plasma generation in a water droplet and optical breakdown in air." Such capabilities would have important use in the development of "laser applications such as atmospheric communications."

Between 2010 and 2015, the ACMS team was part of an AFOSR-funded multidisciplinary university research initiative (MURI) that involved multiple universities and produced 110 papers over a five-year period. The MURI enabled the ACMS team to scale up the performance of its UPPE solver on parallel machines, and the resulting code was shared with and adopted by leading research groups worldwide.

The ACMS team also received AFOSR funding for experiments and theoretical modeling related to near-IR filamentation science. As early as a 1997 atmospheric femtosecond lidar demonstration, the ACMS group had predicted characteristics of near-IR high-intensity filaments. Under AFOSR support from 2015 to 2019, the Arizona group discovered a method to delay filamentation using semiconductor theory, which produced more dilute plasmas due to strong interactions arising from many-body Coulomb effects. This, in turn, allowed for longer duration intense picosecond pulses, corresponding to multi-terawatts of power and multiple joules of energy, to be transported over kilometer distances with very low losses. More recently, UPPE has been applied to modeling pulse propagation in optical fibers, including multimode gain fiber amplification.



UPPE modeling has shown that long-wave infrared ultrashort pulses can shatter water droplets and potentially be used to locally clear fog or clouds in the atmosphere.

A. Nakdee / Getty Images

Taken together, from the sustained rate of increase in the number of citations of the foundational UPPE publications over a 20-year period to the varied applications of UPPE across the field of nonlinear optics, atmospheric science and laser physics and engineering, the evidence shows that the development of UPPE has fundamentally transformed our understanding of how ultrafast, intense laser pulses interact with nonlinear media. OPN

The authors thank Enrique Parra (US Department of Energy), Miroslav Kolesik and Jerome (Jerry) Moloney (both at University of Arizona, USA) for their assistance with the preparation of this article. The research for this article was supported in part by Doran's appointment to the NRC Research Associateship Program at AFOSR (AFRL), administered by the Fellowships Office of the National Academies of Sciences, Engineering and Medicine.

Connemara Doran (connemara.doran.1@us.af.mil) and Arje Nachman are at the Air Force Office of Scientific Research AFRL/AFOSR.

References and resources: **optica-opn.org/link/UPPE**

References and Resources

"Charles H. Townes. Facts." Nobel Prize Outreach 2026. Accessed 1 Feb. 2016. https://www.nobelprize.org/prizes/physics/1964/townes/facts/.

"The Nobel Prize in Physics 2023." Nobel Prize Outreach 2026. Accessed 1 Feb. 2016. https://www.nobelprize.org/prizes/physics/2023/summary/.

A. Braun et al. "Self-channeling of high-peak-power femtosecond laser pulses in air." Opt. Lett. **20**, 73 (1995).

M. D. Perry and G. Mourou. "Terawatt to petawatt subpicosecond lasers." Science **264**, 917 (1994).

"Gérard Mourou. Facts." Nobel Prize Outreach 2026. Accessed 1 Feb. 2016. https://www.nobelprize.org/prizes/physics/2018/mourou/facts/.

B. Miao et al. "Electrons see the guiding light." Physics Today **76**, 54 (2023).

C. Day. "Experiments Detail How Powerful Ultrashort Laser Pulses Propagate Through Air." Physics Today **54**, 17 (2001).

A. Valenzuela et al. "Recent advancements in ultrashort pulse lasers shed new light on directed energy applications." DSIAC Journal **4**, 25 (2017).

M. Mlejnek et al. "Dynamic spatial replenishment of femtosecond pulses propagating in air." Opt. Lett. **23**, 382 (1998).

M. Mlejnek et al. "Optically turbulent femtosecond light guide in air." Phys. Rev. Lett. **83**, 2938 (1999).

F. Courvoisier et al. "Ultraintense light filaments transmitted through clouds." Appl. Phys. Lett. **83**, 213 (2003).

M. Kolesik et al. "Unidirectional optical pulse propagation equation." Phys. Rev. Lett. **89**, 283902 (2002). AFOSR grant #s: F49620-00-1-0312 and F49620-00-1-0190.

M. Kolesik and J. Moloney. "Nonlinear optical pulse propagation simulation: from Maxwell's to unidirectional equations." Phys. Rev. E 70, 036604 (2004). AFOSR grant #: F49620-03-1-0194.

J. Wahlstrand et al. "Bound-electron nonlinearity beyond the ionization threshold." Phys. Rev. Lett. 120, 183901 (2018).

A. Rudenko et al. "Plasma-free water droplet shattering by long-wave infrared ultrashort pulses for efficient fog clearing." Optica **7**, 115 (2020). AFOSR grant #s: FA9550-19-1-0032 and FA9550-18-1-0368.

FY'10 AFOSR, Multidisciplinary University Research Initiative (MURI) [Final report] "Mathematical modeling and experimental validation of ultrafast nonlinear light-matter coupling associated with filamentation in transparent media." AFOSR Grant #: FA9550-10-1-0561.

Y.-H. Chen et al. "Accurate modeling of ultrafast nonlinear pulse propagation in multimode gain fiber." J. Opt. Soc. Am. B **40**, 2633 (2023).