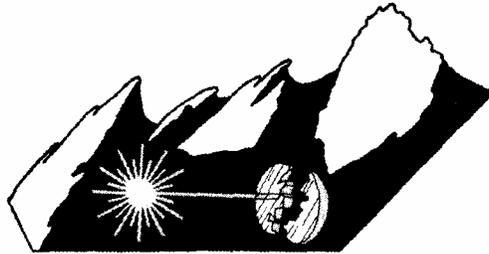


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Proceedings

LASER-INDUCED DAMAGE IN OPTICAL MATERIALS: 2006



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Editors

Gregory J. Exarhos, Arthur H. Guenther, Keith L. Lewis
Detlev Ristau, M. J. Soileau, Christopher J. Stolz

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Foreword

This volume contains the papers presented at the 38th Annual Symposium on Optical Materials for High-Power Lasers, held at the National Institute of Standards and Technology in Boulder, Colorado, 25–27 September 2006. The symposium was cosponsored by the Lawrence Livermore National Laboratory (USA) and the Pacific Northwest National Laboratory (USA). Cooperating organizations included the Center for High Technology Materials at the University of New Mexico (USA), Laser Zentrum Hannover e.V. (Germany), the National Institute of Standards and Technology (USA), Electro-Magnetic Remote Sensing Defence Technology Centre (United Kingdom), and the College of Optics, CREOL and FPCE, University of Central Florida (USA). The symposium was attended by 143 participants hailing from Canada, China, India, Israel, Lithuania, France, Germany, Japan, the United States, and the United Kingdom. Almost one-third of the attendees and more than half of the presentations were from abroad. A mini-symposium focused on the performance of optics in hostile environments was scheduled for Tuesday morning. All told, 81 papers were presented, including oral and poster presentations plus the mini-symposium.

The meeting offered an opportunity to make many new acquaintances. As usual, the National Institute of Standards and Technology in Boulder, Colorado, offered a setting conducive to interchanges between individuals working in closely related and complementary fields. We look forward to future opportunities at this symposium to discuss the latest advances in understanding the laser damage process. The symposium was divided into four traditional sessions devoted to the following topics: thin films; fundamental mechanisms; materials and measurements; and, surfaces, mirrors and contamination. A mini-symposium on ‘Optics in a Hostile Environment’ also comprised the meeting. Dr. Gregory J. Exarhos of Pacific Northwest National Laboratory (USA), Dr. Arthur H. Guenther of the Center for High Technology Materials at the University of New Mexico (USA), Dr. Detlev Ristau of the Laser Zentrum Hannover e.V. (Germany), Dr. Christopher J. Stolz of the Lawrence Livermore National Laboratory (USA), Dr. Keith L. Lewis of the Electro-Magnetic Remote Sensing Defence Technology Centre (UK), and Dr. M. J. Soileau, Vice-President of Research at the University of Central Florida (USA) cochaired the symposium.

The editors assume full responsibility for the summary article, which contains a highlighted overview of the symposium. The manuscripts for papers presented at the symposium have been prepared by their authors. Questions pertaining to their content should be addressed to those authors. The interested reader is referred to the bibliography at the end of the summary article for general references to the literature of laser damage studies.

The 39th Annual Symposium of this series will be held in Boulder, Colorado, 24–26 September 2007. A concerted effort will be made to ensure a closer liaison between the high-peak-power and high-average-power laser damage communities, as well as to include damage issues related to multi-institution research efforts and commercial laser applications. Identification of the mini-symposium topic is currently underway.

The principal topics to be considered as contributed papers in 2007 do not differ markedly from those enumerated above. We expect to hear more about improved scaling relations as a function of pulse duration in the femtosecond range, area, and wavelength down to the x-ray region, and to see a continuing transfer of information from research activities to industrial practice. New sources at shorter wavelengths continue to be developed, and a corresponding shift in emphasis

to short-wavelength and repetitively pulsed damage problems is anticipated. Fabrication and test procedures will continue to be developed, particularly in the area of thin films. New materials and the implication of defects on the damage process will undoubtedly be emphasized, as will further reports on conditioning effects and damage repair or mitigation. More papers on high-energy lasers, space-based optics, and nonlinear optical phenomena also are anticipated.

As was initially established in 1992, several distinguished invited speakers will be identified and invited to make presentations of a tutorial or review nature; in addition, late-breaking developments of interest to the attendees will be covered in other contributions.

The purpose of this series of symposia is to exchange information about optical materials for high-power/high-energy lasers. The editors welcome comments and criticism relevant to this purpose from all interested readers.

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International Program Committee

The cochairs of this series of symposia rely heavily on an International Program Committee to ensure their awareness of significant research in the broad field of laser-induced damage throughout the world. Its members are also frequently the source of suggestions for invited speakers and mini-symposium topics and leaders. The committee performs a vital service as an outreach for the conference on a global scale. Individuals with suggestions for the meeting are requested to contact any committee member (next page) who is either an acquaintance or in close proximity. The committee is ably led by Keith Lewis, International Program Committee Chair.

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Symposium Welcome

On the Occasion of the Thirty-Eighth Boulder Damage Symposium

Gregory J. Exarhos

Pacific Northwest National Laboratory (USA)

The conference cochairs extend a fervent welcome to participants in the 38th Annual Symposium on Optical Materials for High Power Lasers held at the NIST facility in Boulder, Colorado. Significant contributions from the global scientific community continue to both enrich the technical content of the meeting and contribute to its vitality. The international program committee has been instrumental in promoting this conference worldwide, attracting scientists and engineers from more than a dozen different countries. We acknowledge these key contributions in this series of the Proceedings of SPIE that archive significant research results in the laser damage to optical materials field. The Proceedings of SPIE comprises an important resource for collecting the latest results pursuant to laser-induced optical damage, and we gratefully acknowledge the efforts of the authors in both preparing oral and poster presentations and contributing manuscripts to these proceedings.

This symposium is structured so as to promote camaraderie among the participants in a number of ways. All oral talks are presented in one ongoing session for the three-day meeting that not only localizes the attendees to one conference room, but also encourages more extensive participation in the question and answer session following each presentation. A relatively uninhibited audience promotes lively exchanges that probe the scientific content of the talks, often leading to new directions for follow-on research and development. Audience responses are recorded, transcribed, and appear in the proceedings following each oral paper. Six poster sessions, geared to the subject content of the oral presentations, were offered this year, and in the inimitable conference tradition, the presenters were invited to provide a succinct overview of their posters midway through the morning oral sessions. In addition, ample time was provided for viewing the posters and networking among the participants. This approach contributes to the strength of the meeting and, indeed, promotes international exchanges in the laser-damage and related technical communities.

Four subject areas comprise core topics within the symposium. These include: thin films; materials and measurements; fundamental mechanisms; and surfaces, mirrors, and contamination. The last subject area has been modified this year to recognize the critical aspect of optic contamination on laser damage processes. To insure that the meeting is indeed dynamic, a mini-symposium is offered each year in a subject area of current interest to the laser-damage community. This year the focus was on optics in a hostile environment. Key issues in this current technical program that are distributed among the respective topical areas, tend to emphasize shorter wavelength irradiation and ultrashort pulsewidths. Presentations related to these topics are expected to be even more prevalent in subsequent symposia.

The cochairs gratefully acknowledge the untiring efforts of the SPIE staff, Susie McGuire, who also transcribes the recorded question and answer sessions following each oral presentation, and Joan Guenther, conference treasurer. The organizers also acknowledge the efforts of the NIST Staff, Gordon Day, Wendy Ortega, and our technical contact, Kent Rochford, who assist with

coordinating activities and arranging for audio/video facilities in the NIST auditorium. Financial support for this meeting has been graciously provided by the meeting cosponsors, Lawrence Livermore National Laboratory and Pacific Northwest National Laboratory.

The venue for this annual fall meeting, known to most of us as the Boulder Damage Symposium, continues to be located in this beautiful region of Colorado famous for its close proximity to the mountains and an abundance of hiking trails and other recreational activities. The cochairs welcome you to this meeting and wish you all a most productive and enjoyable visit to Boulder. An invitation to you and your colleagues to participate in the meeting again next year is enthusiastically extended.

Summary of Meeting

Laser-Induced Damage in Optical Materials
38th Annual Symposium
25–27 September 2006

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Abstract

These proceedings contain the papers presented as oral and poster presentations at the 38th Annual Symposium on Optical Materials for High-Power Lasers. The conference was held at the National Institute of Standards and Technology facility in Boulder Colorado on 25–27 September 2006. The symposium was divided into the traditional sessions devoted to the following topics: thin films; surfaces, mirrors and contamination; fundamental mechanisms; materials and measurements; and finally, a mini-symposium on optics in a hostile environment. Dr. Gregory J. Exarhos of Pacific Northwest National Laboratory (USA), Dr. Arthur H. Guenther of the Center for High Technology Materials at the University of New Mexico (USA), Dr. Keith L. Lewis of Electromagnetic Remote Sensing Defence Technology Center (UK), Dr. Detlev Ristau of the Laser Zentrum Hannover e.V. (Germany), Dr. M. J. Soileau, of the University of Central Florida (USA), and Mr. Christopher J. Stolz of the Lawrence Livermore National Laboratory (USA), co-chaired the symposium.

All told, 81 papers were presented, including oral and poster presentations plus a mini-symposium. No parallel sessions were held, allowing the opportunity to discuss common research interests with all the presenters. With 143 participants attending, the meeting offered an opportunity to make many new acquaintances. Although held annually in the U.S., this is a truly international conference with 35 percent of the attendees and 50 percent of the presentations coming from abroad. As usual, the National Institute of Standards and Technology in Boulder, Colorado, offered a setting conducive to interchanges between individuals working in closely related and complementary fields. We look forward to future opportunities to again come together there.

The 39th Annual Symposium of this series will be held in Boulder, Colorado, 24–26 September 2007. A concerted effort will be made to ensure a close liaison between the high-peak-power and high-average-power communities, as well as to include damage issues related to various research efforts and commercial laser applications. A mini-symposium related to the subject of optic lifetime issues associated with continuous and high repetition rate lasers is anticipated.

The principal topics to be considered as contributed papers in 2007 do not differ drastically from those enumerated above, although given the amount of interest in contamination over the last few years, the surfaces and mirrors session was renamed surfaces, mirrors, and contamination this year. We expect to hear more about the impacts of contamination on the laser resistance of optical components and the impacts of defects since both of these topics continue to generate significant. High-energy laser windows and crystals continue to place limitations on laser

systems, so remain an active area of research and spirited debate. Refinement of the mitigation strategy consisting of damage initiation followed by arresting damage growth through post-processing techniques is also expected to be a continued focus for next year, as large-aperture fusion lasers manufacture a large number of laser-resistant UV optics. Short pulse laser optics and damage phenomena remain an active area of research. We also expect to hear more about new measurement techniques to improve our understanding of the different damage mechanisms or to improve the manufacturing of optical materials and thin films for optical components of greater laser damage resistance.

As was initially established in 1992, several distinguished invited speakers will make presentations of a tutorial or review nature. In addition, other contributors will cover late-breaking developments of interest to the attendees.

The purpose of this series of symposia is to exchange information about optical materials for high-power/high-energy lasers. The editors welcome comments and criticism from all interested readers relevant to this purpose.

Key words: laser damage, laser interaction, optical components, optical fabrication, optical materials and properties, thin film coatings, contamination.

Introduction

The 38th Annual Symposium on Optical Materials for High-Power Lasers (a.k.a. the Boulder Damage Symposium, because of its Boulder, Colorado, venue) was held 25–27 September 2006. This symposium continues to be the principal U.S. and international forum for the exchange of information relative to the interaction of intense laser light with optical media and components. Historically, the meeting has been divided into four broad categories: thin films; fundamental mechanisms; materials and measurements; and surfaces, mirrors, and contamination as illustrated in figure 1.

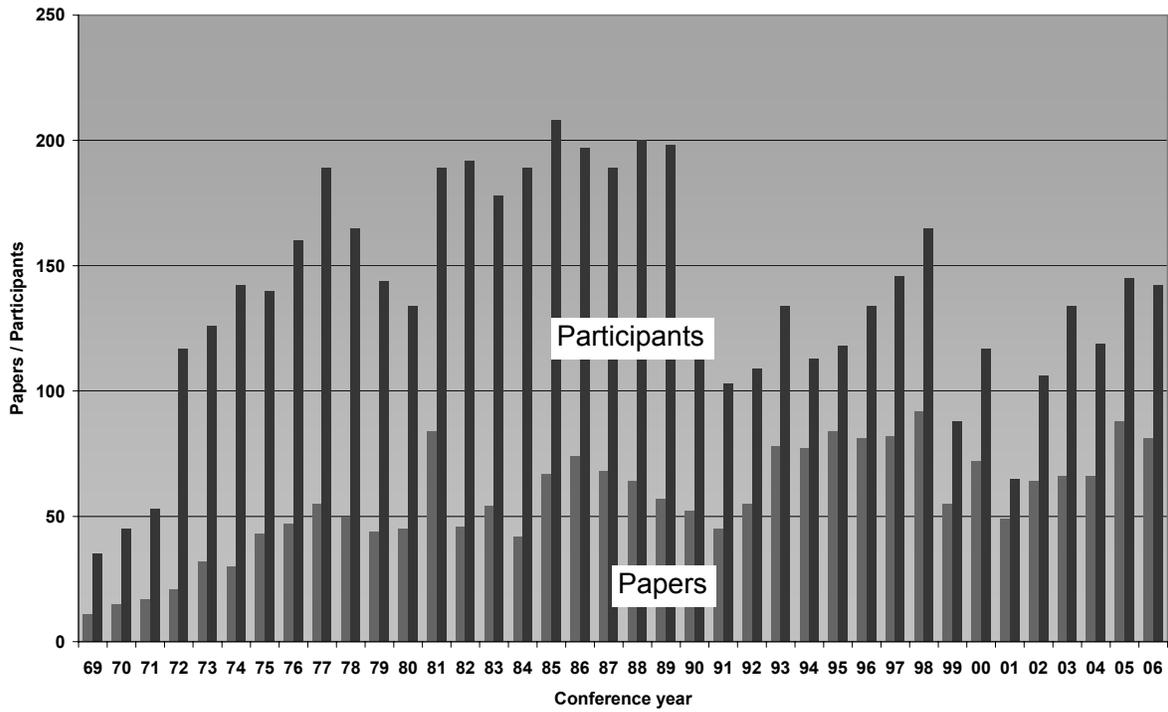
Thin Films

Because of the tremendous range of applications of optical multilayers for modifying the optical performance of elements (e.g., reflectivity, wavelength sensitivities, polarization, or simply protection, etc.), this area is receiving considerable attention at the present time. Besides damage thresholds or sensitivity, topics include advanced thin deposition technology, film structure, film design, film response to environmental attack and aging, and numerous reports on important film properties such as adhesion, thermal conductivity, absorption, stability, defect identification, aging – drift and moisture infusion, and conditioning processes to improve performance.

Dense thin film processes offer the benefit of environmental stability; so much of the research in the field of thin films is proceeding in this direction. Laser interaction studies are uncovering areas where dense films offer advantages over traditional e-beam coatings. An example from the invited talk is the use of magnetron sputtering for nanoscale compensationally modulated coatings to create superlattices and quantum well structures.

Coating defects continue to be an area of active interest in both process optimization, to minimize defect formation, as well as mitigation techniques such as laser conditioning. This year we saw an increase of interest in VUV and XUV coatings.

Boulder conference attendance statistics



Topical emphasis of conference by year

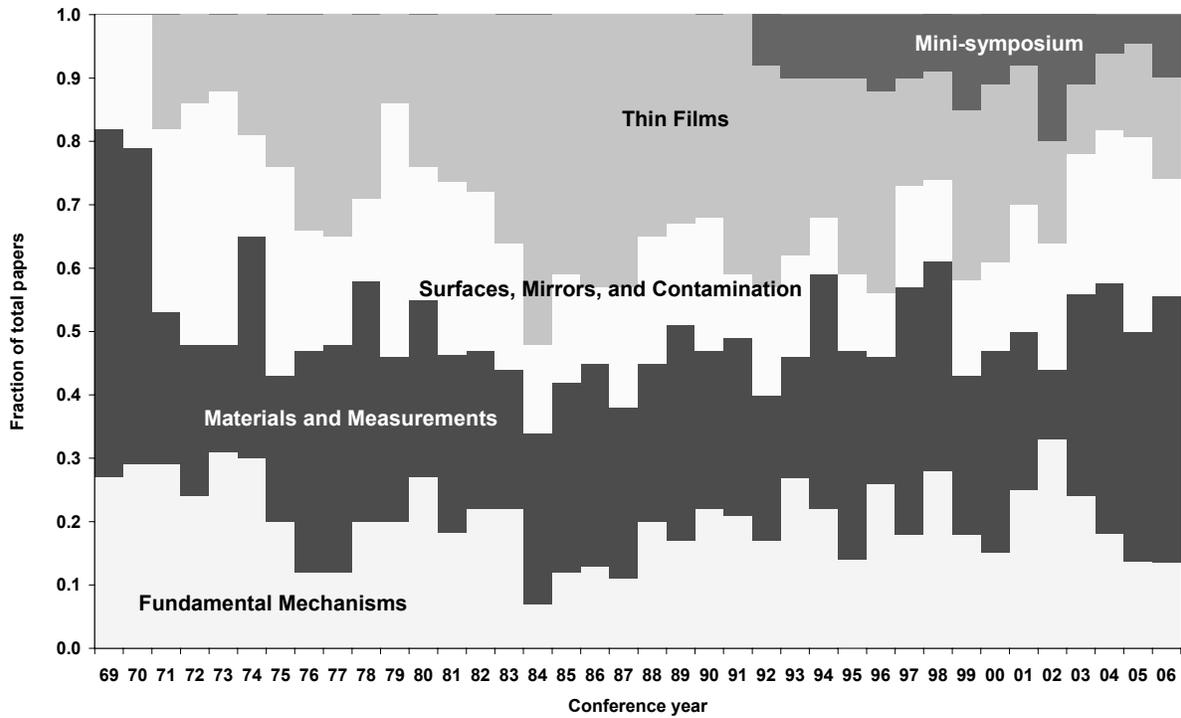


Fig. 1 Historical statistics of conference attendance and paper submission (top) and distribution of submissions by topical area (bottom).

Fundamental Mechanisms

This area deals with the interaction of light with matter – where real system experience is presented. Topics include nonlinear behavior, self-focusing, thermal modeling, and experimental data reduction protocols (e.g. effects of pulse width, repetition rate or duty cycle, spot size, wavelength, temperature, ionizing radiation, and other environmental effects), as well as all types of experimental or material variable scaling relationships that not only afford insight into the fundamentals of the interaction process, but allow extrapolations for engineering and cost-benefit evaluations. In many areas, these insights are based on real-world, systems-level tests, as opposed to a frequently pristine laboratory environment.

Due to the interest in ultrashort phenomena, the invited speaker for the fundamental mechanisms session spoke on femtosecond interaction processes near threshold: damage and ablation. At ultrashort pulselengths, damage mechanisms are driven by solid state physical processes and material properties. Most of the damage research at long pulses (nanosecond and longer) focuses on sub-micron to micron-scale defects (coating nodules, subsurface cracks, absorbing polishing compounds) and thermo-mechanical damage.

Surfaces and Mirrors

Here one will find presentations on surface preparation (including single-point diamond micro-machining and ductile grinding), subsurface damage characterization, roughness and scattering, environmental degradation and aging, as well as substrate material properties, including cooling techniques, and, of course, damage measurements and the cleaning of surfaces. The crux of the contamination problem is fundamentally that damage experiments done in controlled clean laboratory settings do not necessarily yield the same results as laser operations in less pristine operating environments. There is a significant amount of work needed in understanding what contamination is acceptable, what contamination is threatening to optic survivability, and how fluence-limiting or lifetime-limiting contamination can be eliminated or mitigated from operating laser systems.

There was also a significant amount of continued interest in understanding how nano-cluster absorbing defects fluence limit bare and coated surfaces. This topic was covered by an excellent review paper of the topic.

Materials and Measurements

This section deals with laser damage to the bulk of transparent optical media – whether amorphous, polymeric, polycrystalline, or crystalline – and its preparation, as well as reports of material properties of import to their optical function and / or the damage process, e.g., linear and nonlinear refractive indices, absorption, thermal conductivity, stress-optic coefficients, moduli, and defects. Also included are new techniques for measuring these quantities, which present a continuing challenge as materials are improved in quality and diversity.

The topic of crystalline materials continues to be an active area of interest due to their attractive nonlinear properties and high efficiency gain media. Specific crystals that are addressed in this proceedings are KDP, CaF₂, Nd:YAG, RbTiOPO₄, Yb:S-FAP, LiInSe₂, and LiInS₂; laser materials for both commercial and laboratory-scale lasers.

A number of measurement papers dealt specifically with damage test systems that are either new facilities, or new methods in addition to the ISO standard. Finally there continues to be interest in absorption and fluorescence measurements to identify precursors of damage initiators. The invited talk summarized extremely well a variety of non-destructive measurement techniques to examine absorption, scattering, and luminescence of defects that impact laser resistance.

Mini-Symposium on Optics in a Hostile Environment

This year the meeting was concluded with a small mini-symposium dealing with the topic of optics survival in a variety of extreme environments. Of particular interest were the results of the impacts of space environments on a variety of optical samples. Typically during the mini-symposium, a paper will be presented that is marginally relevant to the main topic of the meeting, but is an excellent review of the state of a specific technology. This was especially true for the paper on ophthalmic optics which are exposed to extremely hostile environments, although at extremely low photon flux. The mini-symposium was organized this year by Alan Stewart from The Boeing Company (USA).

Invited Papers

As usual, the 2006 meeting was highlighted by several invited papers. They included:

1. "Femtosecond interaction processes near threshold: damage and ablation," R. Fedosejevs, University of Alberta (Canada).
2. "Using gold nanoparticles as artificial defects in thin films: what have we learned about laser-induced damage driven by localized absorbers?," S. Papernov, University of Rochester (USA).
3. "Recent advances in magnetron sputtered superlattice and quantum well structures," P. M. Martin, Pacific Northwest National Laboratory (USA).
4. "Optical characterization in laser damage studies," M. Commandré, Institut Fresnel (France).

Conference Awards

Beginning with the meeting in 2000, the organizers instituted a best paper award in the oral and poster categories. The awards appropriately take the form of laser-induced art in an optical glass plaque. (see, e.g., paper by I. N. Trotski, Proc. SPIE 4679, 392-399 (2001) plus a remuneration).

Winners selected for 2006 include, for best oral presentation, "Optical characterization in laser damage studies," M. Commandré, J.Y. Natoli, L. Gallais, F. Wagner, C. Amra, Institut Fresnel (France). The best poster presentation went to "Mitigation of growth of laser initiated surface damage in fused silica using a 4.6- μm wavelength laser," G. Guss, I. Bass, V. Draggoo, R. Hackel, S. Payne, Lawrence Livermore National Laboratory (USA); M. Lancaster, P. Mak, Naval Research Laboratory (USA).

In Conclusion

The location in Boulder, Colorado during autumn at the venue of the National Institute of Standards and Technology and its outstanding facilities and support staff, were appreciated by all. The 143 attendees were easily accommodated with ample opportunity to mingle and socialize.

The organizers of the Boulder Damage Symposium look for opportunities to join with other related groups for joint meetings in the future. For example, in 2002 we had a joint meeting with the 7th International Workshop on Laser Beam and Optics Characterization, again with no parallel sessions.

We must also take note of the seamless transition of the administrative functions of the symposium to SPIE. Their presence, experience, resources, and professionalism clearly were made manifest with on-line reservations, payment by credit cards, badges, preparation of the abstract book and pocket programs, and on-line document service, to which we may add the social functions – thanks to them, “A good time was had by all.”

Acknowledgments

A number of volunteers help tirelessly with some of the administrative duties necessary to put on a conference of this magnitude. Joan Guenther continues to handle the residual financial assets of Laser Damage Conference, Inc., because the accountant for our nonprofit corporation resides in New Mexico. Susie McGuire, Administrative Assistant to Greg Exarhos, assists with transcriptions of technical questions asked at the end of each talk. Susie also assisted SPIE staff at the conference with registration, setup, and general questions.

Of course, we are all indebted to Kent Rochford, Division Chief of the Optoelectronics Division, who was the prime contact at NIST, for his continued support and encouragement, and Wendy Ortega, also of NIST, who together made it possible to hold a seamless meeting. On behalf of all the organizers and attendees, we thank them for their tireless efforts.

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