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Interball Mission Generates Results on Magnetospheric Dynamics and Magnetosphere-Ionosphere Interaction

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The Interball project was an international solar-terrestrial science program conducted by the Russian space agency in the second half of the 1990s [*Zelenyi*, 1997]. Interball-Tail (Interball-1), with an apogee of 200,000 km, perigee of 500 km, and inclination of ~63° was targeted at studies of the solar wind, the magnetotail, and the outer magnetosphere. Interball-Auroral (Interball-2), with an apogee of 20,000 km and the same inclination, was targeted at studies of the inner magnetosphere and the auroral zone.

Interball-Tail was launched on 3 August 1995 and entered the atmosphere in October 2000 in a fully functional state. Interball-Auroral was launched on 29 August 1996 and operated for 2.5 years. The Space Research Institute of the Russian Academy of Sciences was primarily responsible for the program. Sub-satellites provided by the Institute of Atmospheric Physics of the Czech Republic were detached from both Interball spacecraft shortly after the launch and remained within several thousands of km from the mother spacecraft throughout the flight.

The spacecraft payload included magnetic field, plasma wave, and particle instruments that were built with broad international cooperation; many European, Canadian, and Cuban institutions participated. A few U.S. scientists have been involved in data analysis as guest investigators.

Interball joined a unique constellation of International Solar-Terrestrial Program satellites—Wind, Polar, SOHO, Geotail—as well as many other associated missions launched in 1992–2000 and a vast network of ground stations. The international cooperation was coordinated under the umbrella of the Inter-Agency Consultative Group (IACG), a forum of four major space agencies tasked with coordinating scientific programs.

During these years, the quantum leap in observational data quantity and quality was reached through comprehensive instrumentation and continuous and simultaneous observations in all domains critical for the understanding of solar-terrestrial coupling, from the Sun to the ionosphere. Interball measurements were promptly available to the scientific community via the Common Data Analysis Web facility at the NASA Goddard Space Flight Center.

More than 500 scientific papers were written with the use of Interball measurements, mostly in international co-authorship. Interested readers could refer to special issues of *Annales Geophysicae* (no. 5, 1997; no. 9, 1998; and no. 3, 2002), and to *Cosmic Research* (nos. 1, 3, and 6, 1998; no. 6, 1999; no. 5, 2000; no. 4, 2002). Some of the most interesting results are presented below (also see *Dubouloz et al.* [1998]). The full list of Interball-related references can be accessed at http://iki.cosmos.ru/interball.

The Magnetospheric Dynamics

The Earth's magnetosphere is observable only by means of in-situ satellite experiments. The magnetosphere is shaped by the solar wind flow, but its global internal dynamics—slow convection, and transient activations such as sub-storms or storms—are controlled by the interplanetary magnetic field (IMF) via the magnetic reconnection process [*Kivelson and Russell*, 1995].

Since magnetospheric structure is ever-changing due to solar wind variations and intrinsic variability, the single spacecraft is not capable of disentangling spatial and temporal changes. Therefore, satellite pairs such as Interball [*Šafránková et al.* 1998], and currently, the four-spacecraft Cluster were used to restore local spatial structure. A large-scale structure can be revealed, involving satellites at different orbits across the magnetosphere. Interball-Tail observations, in combination with other projects' data, were used to resolve large-scale dynamics of the boundary layers [*Sibeck et al.*, 1999], the solar wind [*Zeleny et al.*, 2002], or the magnetotail.

In particular, multi-spacecraft observations help to study sub-storms—bursty releases of energy that accumulate in the Earth's magnetotail when the interplanetary magnetic field

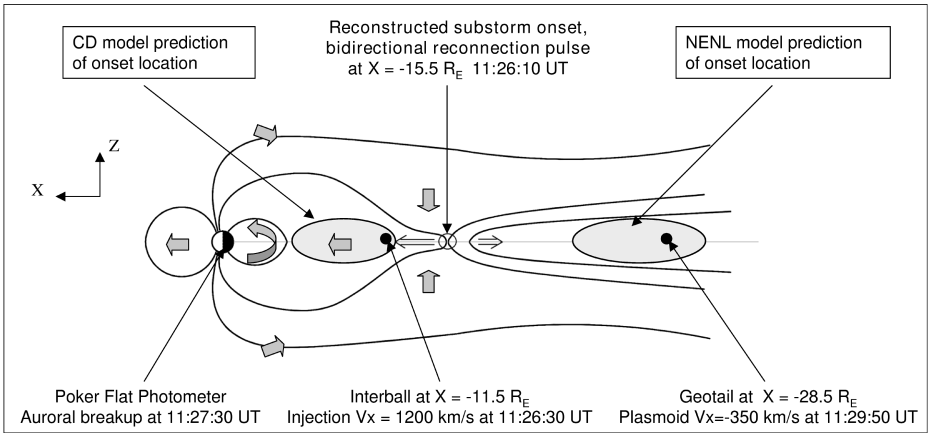

Fig. 1. Reconstruction of the sub-storm onset timing and location is shown, based on the flow measurements by Interball-Tail, the Geotail spacecraft, and the ground auroral breakup on 28 November 1995. The magnetotail structure is shown schematically, along with predictions for onset location by several sub-storm models. Thick gray arrows show the global slow convection pattern in the magnetosphere under southward IMF. In the upper left corner, the geo-solar-magnetospheric (GSM) coordinate system is shown. X is sunward direction; Z is vertical, perpendicular to X, and in the same plane as the geomagnetic dipole axis.

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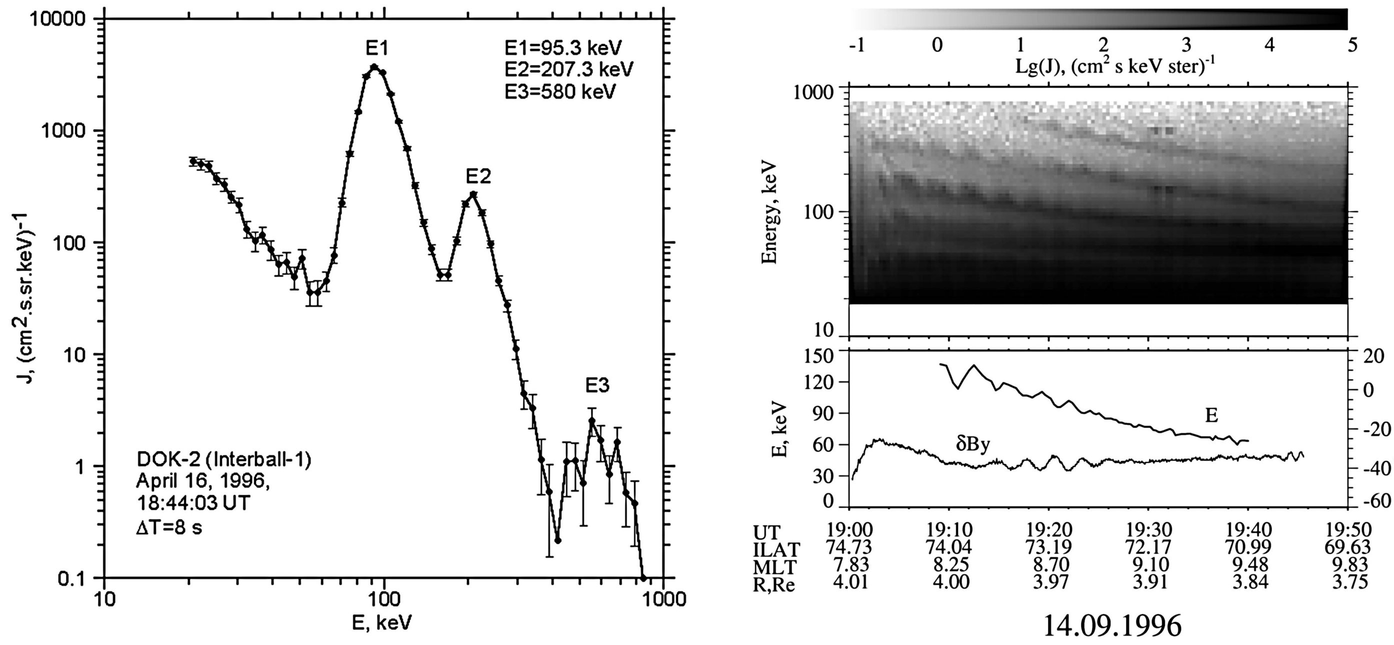

Fig. 2. (left) The three-peaked AMI ion spectrum (Interball-Tail). (right) Wavy energy dispersions in the spectrum. Three injections are visible. Peak energy and local east-west magnetic field variations (Interball-Auroral) are compared.

(IMF) is southward, and which manifest themselves at the ground via irregular geomagnetic variations and aurora borealis in the polar regions. Sub-storm initiation models, suggesting different spatio-temporal scenarios of sub-storm development, are probably one of the most debated topics in magnetospheric physics. Current disruption (CD) and near-Earth neutral line (NENL) models advocate magnetotail-located onset, starting either with the cross-tail current sheet collapse at distances 8–12 R_E from Earth (the former), or with the magnetic reconnection pulse at 25–30 R_E (the latter), while the magnetosphere-ionosphere coupling (MIC) model suggests that sub-storms are initiated in the ionosphere.

Since most of the events in the magnetotail are ordered along magnetic field lines stretched downtail, favorable spacecraft mutual placements are at the same magnetic local time and have a ground observing station at the foot point of this line in the ionosphere. Such a configuration might help to reconstruct the spatio-temporal sequence of events, and hence, cause-and-effect relationships. In Figure 1, one such occasion is schematically shown [*Petrukovich et al.*, 1998], when two spacecraft—Interball-Tail and Geotail—were almost at the midnight meridian to study the small sub-storm that commenced at the same local time at 11:27:30 UT, according to ground observations at the Poker Flat range in Alaska. The Earthward plasma flow (injection), observed by Interball at 11.5 R_E downtail, and the tailward plasma flow (plasmoid), observed by Geotail at 28.5 R_E downtail, could be interpreted as bi-directional plasma streaming from the magnetic reconnection pulse located somewhere between. In a simple one-dimensional approximation, the flows were traced back in time and the pulse origin was located at ~15.5 R_E downtail and 11:26:10 UT, one minute before the earliest ground signature—auroral breakup.

Therefore, in accordance with the dominant opinion, first sub-storm signatures appeared in the magnetotail rather than in the ionosphere. However, the location of this onset contrasts with those of CD or NENL model predictions. It advocates a scenario with the reconnection-driven onset, but indicates its occurrence closer to the Earth.

Plasma Convection

Several new results were obtained due to the original design of some Interball instruments. The first example concerns measurements of global plasma convection or slow average motion in the magnetosphere, which is believed to be driven primarily by the electric field through the interaction of the geomagnetic field with the IMF and solar wind flow (interplanetary electric field). Under southward IMF, plasma and magnetic flux enter the magnetosphere via high-latitude regions, convect in the magnetotail toward the equatorial plane, and then flow toward and around the Earth, returning to the dayside (see thick, gray arrows in Figure 1). Convective flows are hard to measure, since they are much smaller than local flow fluctuations, and, to obtain a statistically significant value, almost all of the mission's observations should be averaged. Observations of flow component along the spacecraft spin axis are most susceptible to instrument errors.

Consistent with this model picture, the pattern of horizontal mean flows in the equatorial plane of the magnetotail was revealed earlier by ISEE-2 and AMPTE/IRM spacecraft. The vertical (along GSM Z axis, Figure 1) component of convection in the magnetotail remained unobservable until Interball, because spin axes of the previous craft were vertical, while the Interball axis was pointing sunward. The Interball-Tail set of magnetotail measurements was divided in four bins for southward/northward IMF, and spacecraft location above/below the equatorial plane. For southward IMF, the mean vertical velocity was found to be ~7 ± 3 km/s toward the equatorial plane, while for northward IMF, it vanished [*Petrukovich and Yermolaev*, 2002].

Such IMF dependence conforms with the model view; however, 7 km/s is two times smaller than the value expected for our data set: 16 km/s (calculated as the drift in the measured local magnetic field and expected local electric field, equal to 10–15% of the interplanetary electric field). This difference might be explained by a robustness of the bulk-averaging approach in the presence of a variety of other latent factors and non-uniformity of the magnetotail.

Plasma Acceleration

While magnetospheric plasma convection is dominated by the core of particle energy distribution function, at energies above the thermal one (~1–10 keV in the outer magnetosphere), distributions are often thought of as "tails"—relatively featureless power-law energy spectra. Such tails are thought to be formed by various mechanisms, such as a leakage from the inner magnetosphere, acceleration on the Earth's bow shock, betatron acceleration in the magnetotail, etc. New information on energetic particle distributions in the magnetosphere was provided by the Interball instrument DOK-2 onboard the Tail and Auroral satellites. It measured ions and electrons in the range of 20–800 keV; energy resolution was at 56 steps.

DOK-2 onboard Interball-Tail observed almost mono-energetic ion (AMI) events—transient ion bursts with narrow energy peaks in the solar wind or the magnetosheath that were never reported before [*Lutsenko and Kudela*, 1999]. Figure 2 (left) presents an example of

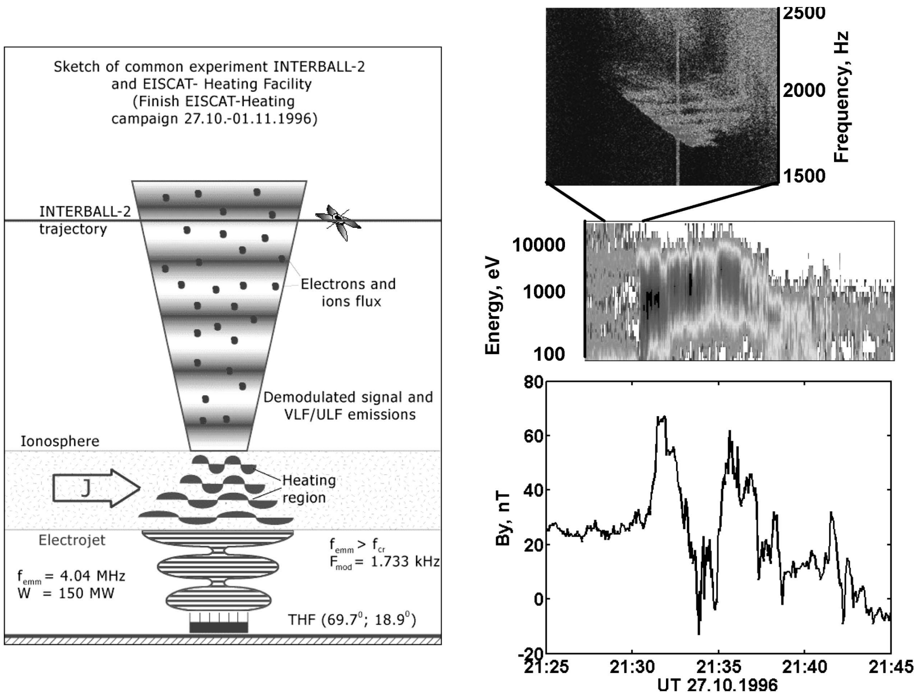

Fig. 3. (left) High-frequency radio waves heat the ionosphere at altitudes of ~100 km and generate hot particle outflow and electromagnetic emissions propagating upward. (right) The electric field frequency spectrogram (top), electron energy spectrogram (middle), and local dawn—dusk magnetic field variation (bottom, main magnetic field subtracted) detected by the Interball-Auroral satellite above the heating facility on 27 October 1996 are shown. Colors on spectrograms from black to white denote intensity in arbitrary units.

the AMI spectrum, observed upstream of the Earth's bow shock. Three peaks likely correspond to H$^+$, He^{+2}, and CNO$^{+5\text{-}6}$ ions, which passed the same electric potential difference, ~100 kV. In most recorded events, however, only one or two first peaks were visible. This ion composition was directly confirmed on several occasions by the Geotail EPIC experiment. Almost all events were registered when IMF was southward. For effective ion acceleration by an electric field orthogonal to the magnetic field, the scale length of the active region should be less than the typical particle cyclotron radius (~1000 km). Electrons are not usually accelerated, since their cyclotron radius is very small.

Since potential difference of about 100 kilovolts is of the order of the maximal (dawn-dusk) voltage available in the Earth's magnetosphere, the AMI generation is likely related to modification of some large-scale structure. In contrast to known acceleration mechanisms involving inductive electric fields, *Lutsenko* [2001] suggested electrostatic acceleration in the electric field bursts, generated during electric current filament disruption (reconnection in the alternative terminology); e.g., at the magnetopause or through collisions of IMF discontinuities in the solar wind. It should be remembered that magnetic field discontinuities in space plasmas (such as the magnetopause) might be also thought of as electric current sheets.

Another new, interesting phenomenon was detected by the DOK-2 instrument onboard the Interball-Auroral satellite in the inner magnetosphere. Particles, sporadically injected from the magnetotail during sub-storms, drift here around the Earth. In the simplest approximation, the time of arrival of an ion to the point of observation (drift velocity) depends on its energy. Since injections are relatively localized in space and time, and higher-energy particles arrive first, a satellite finally measures characteristic "tails" on energy-time spectrograms.

Injections are rather ubiquitous magnetospheric features, but on several occasions, oscillatory variations of energy of incoming ions were observed, so that energy decrease was not monotonic and higher energy particles, which should have passed the spacecraft already, were temporarily returning. Energy variations were accompanied with similar local magnetic field oscillations and geomagnetic pulsations on the ground [*Lutsenko et al.*, 2002] (Figure 2, right). Such variability of incoming particle flux could be explained, for example, by the azimuthal motion of the magnetic flux tubes participating in the pulsation and higher-energy ions returning with the relevant flux tubes. This phenomenon might be a useful tool for uncoupling spatial and temporal scales of geomagnetic pulsations, and is currently under theoretical and modeling investigation.

Magnetosphere-Ionosphere Interaction

Coupling between the magnetosphere and the ionosphere—acting along magnetic field lines by means of electric currents, particle precipitation, and outflow—is one key element of the global dynamics. Magnetospheric domains often communicate more efficiently via the ionosphere, taking advantage of high conductivity along magnetic field and ionospheric current systems. Thus, a sort of feedback or relay connection is introduced in the magnetospheric activity; for example, in sub-storms.

Besides passive measurements, active sounding is widely used to probe the ionosphere. A number of powerful ground-based facilities have been built in Russia, Scandinavia, and the United States; these are capable of inputting megawatts of radio wave power into the ionosphere. Such energies already might be sufficient to modify coupling properties. In a unique experiment, the magnetic field lines above the EISCAT heating facility in Norway were tested by the Interball-Auroral, located near the local magnetic midnight and at ~8000 km altitude, higher than the ionosphere [*Mogilevsky*, 2002] (Figure 3).

Immediately after the switch-on (at ~21:30 UT), variations of local magnetic field and burst of 0.1–6 keV electrons were registered over the background of the almost-empty flux tube. Simultaneously-detected, cone-like characteristic electromagnetic emission is usually associated with upward electron flux (Figure 3, right). These structures correspond to a downward, field-aligned current connecting the heated spot in the ionosphere and some domain of the magnetotail. This is, to the best of our knowledge, the first direct observation of the artificially-induced, field-aligned current similar to that formed in the course of sub-storms. Whether this current will initiate development of a full natural magnetospheric current circuit or not depends, of course, on a particular state of the magnetosphere. A special mission, Resonance, is being designed now to perform such studies on a more regular basis, rather than using occasional passes.

Future Plans

Two new solar-terrestrial science missions are being considered now in Russia. These would concentrate on several more specific scientific targets. The prime goals of Resonance spacecraft [*Demekhov et al.*, 2003] are investigations of inner magnetosphere dynamics in close cooperation with ground-based facilities. In its unique, magneto-synchronous orbit (perigee 500 km; apogee 27000 km; inclination 63°), the spacecraft will periodically co-rotate with sub-auroral magnetic flux tubes, so that development of plasma processes in the selected tube, preferably having a ground station at its foot point, could be monitored for a period up to 2 hours.

Scientific tasks to be addressed are: the role of plasma waves in acceleration and precipitation of energetic particles; energy transfer from hot to cold plasma component; and the operation of magnetospheric masers in natural conditions and under artificial influence. These fundamental plasma processes are responsible for ring current and outer radiation belt development, outer plasmasphere erosion, and refilling. Besides passive monitoring, an active sounding program is being developed that involves a real-time data transfer to the ground station with the intention of introducing a feedback in the heating process.

Another mission, Interball-3, at the equatorial elliptic orbit with apogee about 300,000–350,000 km, is targeted at outer magnetosphere studies. The spacecraft will spend significant time in the middle magnetotail, where magnetic reconnection and thin current sheets—the physical phenomena central to our understanding of energy conversion and particle acceleration in space plasmas—are quite common. These missions are planned to be implemented in the framework of the International Living with Star program, which is aimed at coordinating solar-terrestrial research during the next decade.

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Revised White House Peer Review Guidelines Draw Generally Favorable Response

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A new bulletin from the White House Office of Management and Budget outlines minimum standards for peer review of scientific information that includes findings representing an official position of a department or agency of the federal government.

The OMB Revised Information Quality Bulletin for Peer Review, released on 15 April, substantially modifies a previous draft issued on 15 September 2003, which some had criticized as restrictive and imbalanced.

The new bulletin requires agencies to undertake peer review of "influential scientific information" before it is provided to the public. The bulletin also sets standards for more rigorous peer review of "highly influential scientific assessments." This category applies to science information that would have a significant impact on public policies or on private sector decisions—in the amount of more than $500 million in any year; or which involve "precedent-setting, novel, and complex approaches, or significant interagency interest."

However, the bulletin provides individual agencies with broad discretion in determining their peer review mechanism. Alternative acceptable forms of review noted in the revised bulletin include scientific information produced by the National Academy of Sciences.

The bulletin specifies that the selection of peer reviewers should, to ensure credibility, be based on expertise, a diversity of scientific perspectives, avoidance of conflict of interest, and independence. The bulletin recognizes that government-funded scientists in universities and consulting firms likely would be able to provide an independent review when an agency grant is awarded through a competitive process that includes peer review.

Exemptions from peer review are provided for the dissemination of sensitive information related to national security and foreign affairs. The bulletin clarifies that it does not cover information products that do not represent the official view of a department or agency of the federal government, even if the information is produced by government-funded scientists. Also not covered is the dissemination of time-sensitive medical, health, and safety information; accounting, budget, and financial information; and routine statistical information.

The bulletin also calls for each agency to publicly post and update its peer review agenda, and requires the OMB Office of Independent and Regulatory Affairs and the White House Office of Science and Technology Policy to form an interagency work group on peer review.

OMB noted that, prior to the development of this bulletin, there had been no government-wide standards for peer review. The bulletin was issued under the federal Information Quality Law of 2000, and what OMB cites as its "general authorities to oversee the quality of agency information, analyses, and regulatory actions."

In a document accompanying the bulletin, OMB noted that "the use of a transparent process, coupled with the selection of objective and independent peer reviews, should improve the quality of government science while promoting public confidence in the integrity of the government's scientific products."

Criticism of Earlier Draft

In December 2003, several members of Congress, including Rep. Henry Waxman (D-Calif.), ranking minority member on the House Committee on Government Reform, had filed comments with OMB labeling the earlier draft as "a wolf in sheep's clothing." They had argued that the draft document would impede efforts to protect health and the environment, because complying with a "burdensome" peer review process would slow down important regulatory initiatives.

They also complained that the document would allow conflicts of interest in the regulatory process by permitting the participation in the peer review process of scientists with ties to regulated industries, while limiting participation of agency-funded experts. The comments from Waxman and his fellow members stated, "This proposal is an unprecedented attempt by OMB to exert control over federal agencies, not a genuine effort to improve the quality of science."

However, William Colglazier, executive officer of the National Academy of Sciences and the National Research Council, said the Academies on the whole are very pleased with the revised bulletin. "We would not be unhappy if this is the final version," he said.

Colglazier indicated that the original draft was very restrictive and rigid, and would not have approved of some standard peer review procedures. He said the new document is much more flexible, leaves a substantial amount of discretion concerning peer review to individual agencies, and recognizes the Academies' peer review standards.

Colglazier said further, that, although OMB often tries to exert control over federal agencies, there is "not a lot of overreach by OMB" in this instance. He noted that although some are worried that additional requirements could add more bureaucracy and slow down the process of approving regulations, it is not clear whether there would be that disadvantage. "The benefits of improved standards on conducting peer review far outweigh additional bureaucracy," he said.

David Shively, assistant professor in the geography department at Central Michigan University in Mount Pleasant, who had expressed disappointment in the draft version, indicated that the language in the revised bulletin is a significant improvement. This version "effectively allays my fears that scientists who work in the not-for-profit sector (i.e., universities, institutes, etc.) and who conduct their research using federally-funded grants would be excluded from participating in agency-sponsored peer review activities."

Shively noted that it is important to include such scientists in the review process because they often work in the area of frontier science, "which implies that they have a strong understanding both of the theory that underlies their work and the implications of their work and findings to society."