

Designing the retina for an eye towards the past!

Dr. Marcel Bruijn of the Space Research Organisation Netherlands designs the smallest components in Comsol Multiphysics

XEUS (The X-Ray Evolving Universe Spectrometer) is a mission being conducted by the European Space Agency (ESA) with the goal of gaining a better view of the universe and the Big Bang. The researchers hope to launch this X-ray telescope within the next decade, and by “looking” at radiation generated millions and millions of years ago, it will give us a far more accurate “eye” to observe the first massive black holes and galaxies that evolved into the clusters we see today (Figure 1). Achieving this goal requires a substantial undertaking. The engineers must design everything from the large scale of the telescope’s mirror or “lens” (10 m in diameter) to the pixels that make up the detector’s “retina,” and do so while paying attention to the smallest details. Scientific software like COMSOL MULTIPHYSICS has made a large contribution in helping the researchers achieve their goals.

BY ED FONTES AND PHIL BYRNE, COMSOL

Figure 1—An artist’s conception of the XEUS telescope. The cylindrical object in the background is the instrument’s free-flying mirror or “lens,” while the gold-colored box contains detector systems plus front-end and digital electronics. It also contains several thrusters to maintain a precise distance (50m +/- 0.25 mm) and orientation relative to the mirror. The telescope will orbit at a distance of several hundred kilometers above the earth. (photo courtesy of the European Space Agency)

Traces of the Big Bang

The ESA is working on several missions to study the evolution of the universe from the time of the Big Bang. Scientists believe that long ago all matter and energy existed in an infinitely small point of infinite density with infinite heat, known as “hot” matter (Figure 2). After the Big Bang, the energy and matter started to distribute itself to create what we now know as the universe. Some of this matter remains extremely dense, in some cases so dense that light cannot escape such as in black holes; this matter’s temperature remains extremely high so even today we still have hot matter. In contrast, the universe we can see with our eyes and traditional optical telescopes is known as “cold” matter because it has undergone constant cooling ever since the Big Bang.

Under the auspices of the Horizon 2000 Scientific Programme, the ESA began launching telescopes and probes to look at the remnants of the radiation from immediately after the Big Bang. For instance, the Planck mission in 2007 will investigate the clumping of matter that took place 300,000 years after the Big Bang.

Approximately a billion years after the Big Bang, the emergence of self-gravity resulted in a hot and a cold universe. The XEUS telescope will investigate this hot universe by looking at the formation of the first black holes as well as galaxy clustering. Because hot matter does not emit visible light, this telescope will gather X-rays to investigate how the evolution of black holes is related to star formation as well as the creation of the first metal elements. This telescope is



Figure 2—It was only approximately a billion years after the Big Bang that “hot” and “cold” matter started to appear. Various space probes (represented by the row on the bottom) will investigate various early stages of the universe.

targeted for launch in January 2014.

The 2-part XEUS telescope will be launched on the Ariane V rocket developed at the European Aeronautical Defense and Space Company (EADS). These two space vessels, basically the telescope’s mirror and detector, will maintain a separation of 50 m, which cannot vary by more than 0.25 mm.

Accuracy at the micro-level

To create XEUS, the ESA is cooperating with commercial entities such as EADS plus governmental labs and academic institutions. Among them is the Space Research Organization Netherlands (SRON) where physicist Dr. Marcel Bruijn is working on the design of some of the smallest components in this complex telescope, specifically, the pixels in the detector.

“Time’s earliest black holes and galaxy clusters leave behind signatures in the form of X-rays that we can measure,” explains Dr. Bruijn. “The detector’s pixels must measure the energy of X-rays coming from millions of light-years away. To do so, the detectors must filter this incoming information out of noise coming from the universe. We can do so in part by maintaining the pixels at a temperature of a few milliKelvin, but good geometric and thermal design is also essential.”

Through these efforts, the researchers hope to increase the telescope’s sensitivity by a factor of 200 and its energy resolution by a factor of 30 over XMM-Newton, the current telescope in operation. After only six years of development, Dr. Bruijn and the Sensor Research and Technology Department at SRON have reached this goal for a single pixel, and they’re close to producing a 5 x 5 pixel-array prototype (Figure 3). Eventually they hope to implement a 32 x 32 pixel array

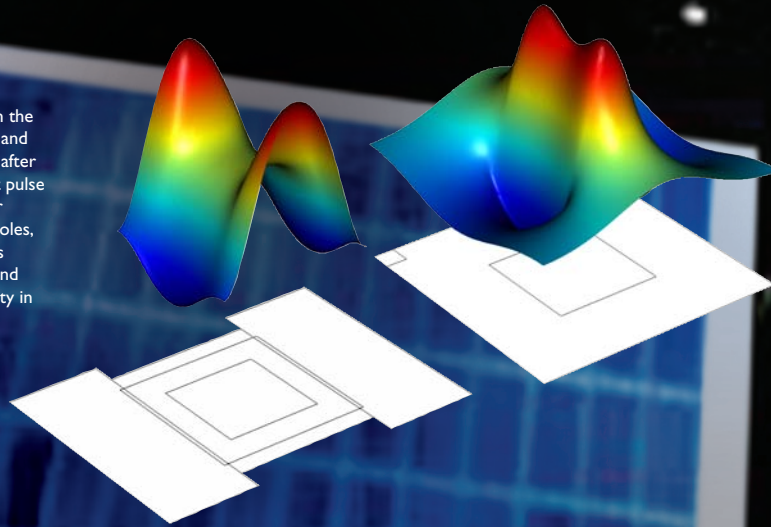
Modeling is imperative

“Reaching our goal within six years was an immense task and partly a direct result of mathematical modeling,” comments Dr. Bruijn. “This progress gives us an opportunity to concentrate on even greater accuracy and resolution for our measuring devices before XEUS launches.”

Rather than build many prototypes in a variety of geometries and materials, Dr. Bruijn mathemati-

“The detector’s pixels must measure the energy of X-rays coming from millions of light-years away.”

Figure 4—Temperature in the absorber (left geometry) and the TES (right geometry) after 300 nanoseconds. A heat pulse is applied to the absorber geometry at one of the poles, and COMSOL Multiphysics calculates the heat flow and subsequent current density in the TES.



cally models the pixel design. As he explains, “We can quickly gauge material suitability through computer simulations, and we can also swiftly assess geometry shapes and thicknesses. Further, modeling has become pertinent not only in optimizing the pixel but also in doing so for the surrounding components.”

The pixel is made from two coupled geometries—an absorber and a superconducting transition edge sensor (TES). In the absorber, X-rays hit a bismuth plate that translates them to heat energy through the movement of electrons and the vibration of the crystalline lattices. Any model of the absorber must consider different relationships in heat capacity and conductivity in order to give an accurate assessment of the heat flux to the lower geometry.

The second geometry acts as a thermometer where heat generated in the absorber affects the electrical conductivity of the TES material (Figure 4). By placing a potential across the sensor, the instrument can calculate the resulting current density. The scientists use this information to calculate the energy of the original X-ray photon. They then obtain the intensity of the incoming X-ray flux by counting electrical pulses.

Flexibility in the software

To model the pixels, Dr. Bruijn’s team used finite-element software, specifically COMSOL Multiphysics. As he notes, “That software allows us to model both

geometries separately while setting up the simulation, and then it solves them simultaneously as a truly coupled problem.”

Another advantage is COMSOL Multiphysics’s equation-based modeling. Adds Dr. Bruijn, “We found it extremely convenient that the software allows us to type in the highly nonlinear equations for heat capacity plus thermal and electrical conductivities for all the materials involved. Some of these relationships include functions of temperature raised to

“Reaching our goal within six years was an immense task we completed partly as a direct result of mathematical modeling.”

the power of five, while others require the derivative of temperature. It was great being able to avoid the work that would otherwise have arisen when trying to force other software to include such arduous and unusual terms.”

Dr. Bruijn also requires simulations in order to include the surrounding measurement system (Figure 5). He elaborates, “We apply a constant bias voltage, and the pixels are affected by the electro-thermal feedback mechanism. When the temperature

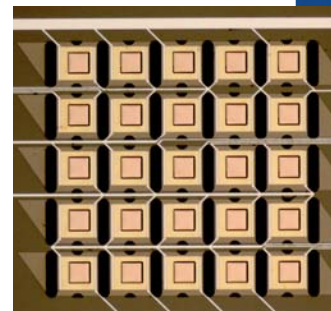


Figure 3—Photograph of a prototype 5 x 5 pixel array. Each pixel contains a copper absorber (the square in the center), a Ti/Au superconducting transition edge sensor (the larger square), and a Si₃N₄ membrane for thermal insulation. Electrical wiring to the pixels runs across narrow beams of silicon, which also form a thermal ground. In a future version, mushroom-shaped Cu/Bi absorbers will replace those made of copper.

KEY FACTS: THE SPACE RESEARCH ORGANIZATION NETHERLANDS (SRON)

As a part of the Netherlands Organization for Scientific Research, SRON is the national center of expertise for the development and exploitation of satellite instruments in astrophysics and earth system science. It acts as the Dutch national agency for space research and as the national point of contact for ESA programs.

KEY FACTS: THE EUROPEAN SPACE AGENCY (ESA)

- Europe’s gateway to space
- 15 member countries, 1920 employees, budget of 2,700 million Euros
- Works closely with space organizations outside Europe
- Headquarters in Paris
- Tracking stations in Europe, Africa and Australia
- FOUR SUBUNITS:
 - ESTEC (Netherlands): design hub for most ESA spacecraft
 - ESOC (Germany): responsible for controlling ESA satellites in orbit
 - EAC (Germany): trains astronauts for future missions
 - ESRIN (Italy): collects, stores and distributes satellite data to ESA’s partners, and acts as the Agency’s information technology center

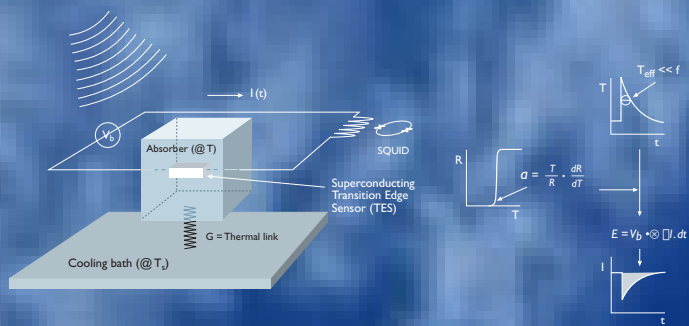


Figure 5—Schematic of the XEUS narrow-field detector. X-rays hit the absorber, which transforms them into heat energy that the TES or “thermometer” then measures. Using an applied voltage bias, any change in TES-material conductivity generates a current that varies with the heat energy provided by the X-rays. A feedback mechanism drives the temperature in the absorber/ TES combination to a setpoint. The entire detector assembly is cooled to a temperature of a few tens of milliKelvin.

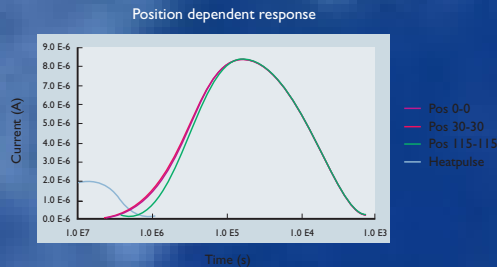


Figure 7—The effect of geometric noise. The same heat pulse is applied at different positions on the absorber, resulting in a different signal for the measurement of the original heat source. Proper layout of the sensor pixel can minimize this noise.

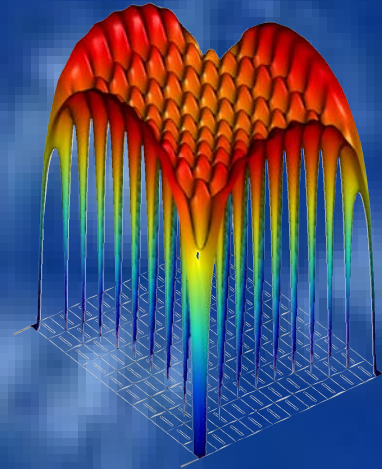


Figure 6—COMSOL Multiphysics plot of temperature in the sensor array. The temperature differences are small, and the position in the array can give rise to noise if the units are not compensated properly for position.

risers, resistance increases, thereby causing less current and less heating. The energy that an X-ray imparts to the electrons and lattice in bismuth is on the order of 10-15 J. Knowing the exact shape of the current pulse is important because we must extract the energy of the X-ray by filtering noise from the pulse. The optimum digital filter depends on the pulse shape.”

Operating the detector at a very low temperature

“COMSOL Multiphysics allows us to model both geometries separately while setting up the simulation, and then it solves them simultaneously as a truly coupled problem.”

(Figure 6) reduces thermal and electronic noise in the TES. However, creating this low-temperature environment is more difficult in a spacecraft being hit by direct sunlight than in a ground-based laboratory. The mission is developing a cooling system that magnetizes and demagnetizes a special salt pill for this purpose.

Yet another type of signal interference to account for is geometric noise—the uncertainty in the land-

ing position of an incoming X-ray photon. “For a given sensor layout,” he continues, “we can calculate the amount of geometric noise, which we cannot directly exclude through filtering. COMSOL Multiphysics helps in designing our layout until we minimize that noise (Figure 7). Once we decide on a layout, COMSOL Multiphysics calculates the pulse shape as a function of X-ray energy. This helps us design a digital-filter template to reduce the effects of electronic and thermal noise in an optimum fashion.”

Small detail allows a bigger picture

The XEUS mission is an impressive project that will observe the wonders of the universe as never before possible. This telescope is a magnificent piece of engineering, in a sense much like the human eye. All the components must work well together, from the largest to the smallest level: the universe is infinitely large; the XEUS mirror is meters in diameter; the detector pixels are 0.25 mm in size; and the measured data are in milliKelvin and electron-volts. ■