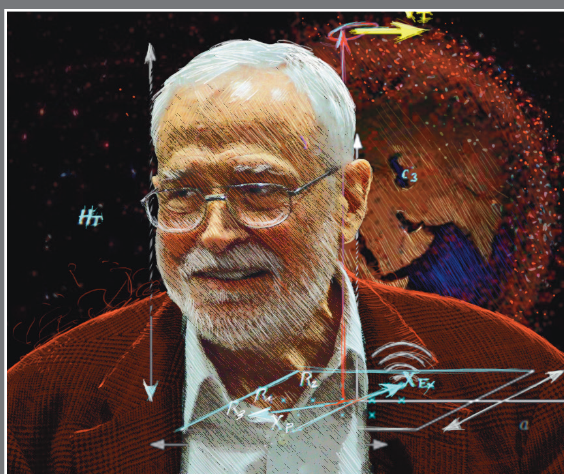
George Papanicolaou

Space Surveillance and Risk Assessment: The Economics of Debris



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Summary

In 2007, China sent a planet-hunter satellite into orbit with the objective of colliding with another satellite. The collision produced the largest amount of space debris in history, capturing the attention of the global community. This incident changed the perception of the dangers of such debris, becoming a serious concern for governments with a space strategy. The awareness, prevention and elimination of such debris have been the object of intense planning and economic activity over the last 12 years. This *Prisme* presents an overview of these developments from the point of view of a scientist in the field of space debris.

The genesis and characteristics of space debris

The story of man-made objects in space started on October 4, 1957, when the first satellite went into orbit. Sputnik was a spherical object with a diameter of 58 centimeters and was put into space at an average altitude of about 500 kilometers, orbiting the Earth within a period of 96 minutes. That represents a speed of 7.6 kilometers per second, the necessary speed for staying in Low Earth Orbit (LEO). Objects, however, cannot stay in orbit forever. They slowly descend due to friction at 500 kilometers' elevation. When the object reaches around 200 kilometers' elevation, the atmosphere takes over, and smaller objects burn up. Low Earth orbit represents a range between 200 and 1500 kilometers in elevation. There are now, 60 some years after Sputnik, roughly 10,000 objects that are big enough (of the order of a quarter of a meter or more) to be tracked and that are being followed constantly. In a geosynchronous orbit, the outer perimeter where things stay in orbit and which is roughly 5 Earth radii from the Earth's surface (about 35,000 kilometers in elevation), there are some 20,000 objects large enough (more than 50 centimeters in diameter) to be tracked. Geosynchronous means that a satellite that reaches that elevation will stay in place relative to the Earth. It makes only one rotation per day, just like the Earth.

These 10,000 objects large enough to be tracked are in an environment of about 170 million pieces of debris the size of one centimeter or larger. They are not uniformly distributed in space. These small debris descend in altitude slowly due to drag, on the scale of decades, especially the ones at higher altitudes where there is less drag. These small objects are fragments from disintegrating larger satellites. They are produced from collisions between satellites and smaller objects, from booster rockets that bring the satellites up into space, and any number of man-made objects in space. They fly at speeds three to four times faster than bullets from high-performance guns. When a 1-centimeter object strikes, for example, a 1-meter satellite, it creates an explosion and all sorts of small objects are generated; they stay in orbit, and the new debris is widely dispersed. Imagine that they are moving in opposite directions at 7 kilometers per second, which means that they collide at a speed of 14 kilometers per second: everything disintegrates in all directions! At that kind of speed, the debris very quickly descend to the speed that keeps them in orbit.

They do not stay at the same level, however, they move up and down depending on their initial speed after the collision.

The study of space debris began some 40 years ago. One of the first highly cited papers was that of the authors Donald Kessler and Burton Cour-Palais in 1978, "Collision Frequency of Artificial Satellites: The Creation of a Debris Belt".[1] The "Kessler effect" was defined in that paper as the possibility that the density of debris in low Earth orbit, or even a little bit higher, increases to the point where the collisions occur so frequently that they become a constant. It is like a sustained nuclear reaction where there are enough neutrons that they reach some critical level of neutron density, so that when they strike each other, a chain reaction occurs. That can happen in space, when there are enough debris so that this fragmentation continues indefinitely, and the entire low Earth orbit and higher space become impenetrable by an object. In other words, the moment the object enters that region, it gets struck by other objects. Figure 1[2] below gives an estimate of the density of flying objects as a function of altitude from about 200 to 2000 kilometers. We see that around 800 kilometers, we have the highest density for flying objects. At the lower altitudes on the graph are the objects that fly at the highest speed to stay in orbit,

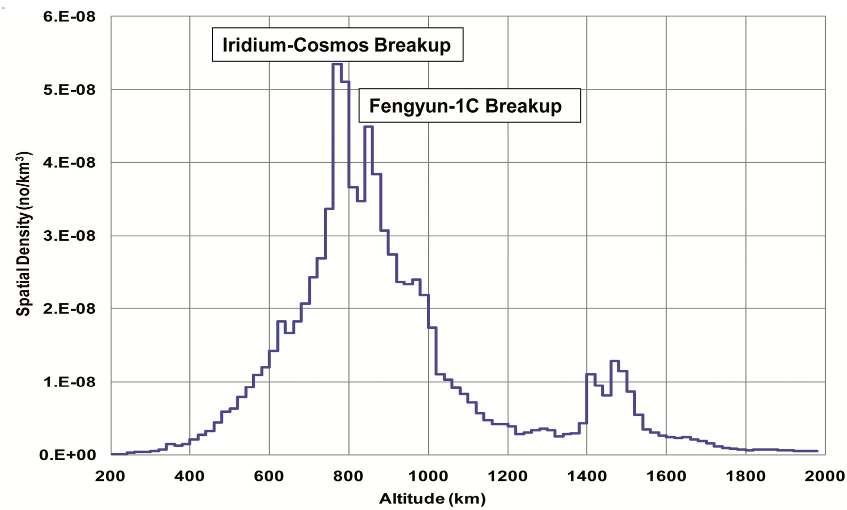

Figure 1: Estimated radial debris distribution (NASA, 2011)

and then descend the fastest into the atmosphere where they burn out. At the higher altitudes of the graph are the objects that descend slower, where they will stay for a very long time in space if collisions or other incidents do not occur. I am not exactly sure why the graph is bimodal. It is assumed that most of the satellites going up are in the first regime. If you want to launch a satellite, you do not want to put it in or near the first curve in the figure; you want rather to put it somewhere where there is much less debris and fewer satellites. The y-axis gives the spatial density of the satellite, but it is not clear how far down in the size of the objects the density has been calibrated.

A new era of space surveillance

A critical event occurred in 2007. China carried out an anti-missile test in space. They sent a planet-hunter satellite into orbit at an elevation of about 800 kilometers, with the objective of colliding with another satellite. It was a mission of destruction: if a hostile object is found at 800 kilometers, how do you eliminate it? The result was that everybody around the globe was horrified. The Chinese did not seriously consider that when you destroy a satellite, you generate debris that will remain in space essentially forever. In this one collision, the largest amount of debris in history was created. In February 2008, the United States destroyed a defective satellite that was believed to be carrying toxic material. It was at an altitude of 250 kilometers, thus close to the boundary where it could enter the atmosphere and burn out, which is, in the end, what happened. The mission was successful, but a very close call. By 2009, most of the debris that was generated had dissipated into the atmosphere below. At the time, however, information about the satellite was needed in order to send something over to destroy it with a minimal amount of debris, and that information was not quite available. The US was, however, able to claim that they had not been as careless as the Chinese, indiscriminately polluting space.

Following that incident, the US government began to realize that the surveillance system put in place in the 1960s had become inadequate. It was based on lower frequencies, the ones used for tracking those 20,000 objects. It was a radar system; the radar beams up energy into the sky, so that the objects up there can reflect back and thus be tracked. That system has not changed much since the 1960s, and it is still operational and in use today. It operates at about 400 megahertz, meaning it has the wavelength of about a meter, like FM radio, so the resolution is low.

A new system has been put in place at a higher frequency, but is not yet fully operational. It has a wavelength of about 12 centimeters, like cell phones. It will have a lot more resolution: instead of tracking some 20,000 objects at low frequency, it will be able to track something close to 200,000 objects at a time using high frequency. We will be able to track objects as small as 10 centimeters, of the order of the wavelength of the radiation that is sent out. Nevertheless, we are now 10 years into its development, and the system is still not fully operational. They were expecting to have it operational first in 2013–2014 and to shut down the old system, but that still has not happened. In 2017, I went to the annual meeting of space scientists in Hawaii, where I learned that the new system functions but still remains far from fully operational.

The economics of space debris

What are the economic aspects of all this? A whole new industry is being built up. We are currently witnessing a transition from something that was completely government controlled to something that is moving into the private sector.

Until about 2014, most of the activity in space for the United States (I do not have figures for Europe, although there is also a lot of activity going on there) was carried out by the US government, mostly by the military and the National Aeronautics and Space Administration (NASA). The military's primary objective is to detect incoming missiles. That surveillance is carried out by an organization that is part of the US Air Force, but very little has been published in the last 40 to 50 years. NASA, on the other hand, is not a secret organization. They are expected to publish, but in practice, they do it infrequently. The first exception to this US government control of everything occurred in 1964 with the launch of a geosynchronous satellite, at an elevation of about 35,000 kilometers, during the Olympic Games in Tokyo. That was the first one to go up for use as a telecommunications satellite, and it was the first time that the Olympic Games were broadcast live into the United States. There are now about 600 geosynchronous satellites for communications and forecasting at that elevation. These are international numbers, not just for the United States. About a quarter of them are alive, and the others are just up there.

In 2014, space was opened up to private enterprise, meaning it became possible for a private entity to launch its own satellite. To do so, all they needed to do was to connect to the US government's website and declare the intent to launch a satellite. There is a questionnaire to fill out: describe your satellite, identify yourself, your business, who is going to launch the satellite for you, where it will be launched, and so on. There exist commercial companies that will put the satellite onto a missile that will carry it up. But what do you think the government wants to know most about your satellite that is going up into space? They want to know the expected lifetime of the satellite, in other words, how long will it stay up in space? Their main concern is to know that by a given date, say in 20 to 30 years, your satellite will be down. If this is the US government's attempt to control who is putting things up into space, it is an incredibly weak initiative for regulating objects in space.

The result of this opening up of the market was an explosion of satellites going up into space. Companies have been created and developed just for that purpose. There is such a company in Palo Alto, California. It has been in business for about five years. It is privately, and very well, funded. It has created a constellation of satellites – close to a 1,000 small satellites – at an elevation of about 500 to 800 kilometers, which are circling the Earth, carrying cameras. The technological added value of this company was to use satellites – the size of a meter or so – and mount them with a camera system with communications equipment that allows you to control the camera and how it is oriented. Several hundred cameras can be mounted onto a satellite constellation; their lenses pointing towards the Earth are coordinated so that they cover a large swath of land rather than just a narrow area, a range of up to 100 kilometers as the satellite moves around the Earth. The technology is similar to taking panoramic pictures with your cell phone when you move the camera horizontally to get a wide-angle. The panoramic image is created by matching up the overlaps. That is the only "imaging" technology of this satellite company. This technique of matching the overlaps of different images is, however, about the simplest and most naive thing you can do in imaging since it does not improve resolution.

Such privately owned and operated satellite constellations have thus been appearing over the last five years to provide large-scale and repeated remote sensing services. Who are the clients of these services? Agriculture is one of the biggest clients:

large farms, big sugar plantations in Brazil, and so on. Agribusiness is very interested in this new technology. The satellites provide a very accurate measure of what is going on every 1.5 hours for tracking crops, for example. It provides incredible precision for the agricultural industry and has become a tool for creating industrial agriculture. Livestock is another example. Given the high resolution of the cameras, you can track individual cows, knowing exactly where they are, where they are going, at any time of day, within the cameras' range. I am not exactly sure what the companies charge, but if you are running a big ranch, if you are in the livestock business, you will want to know exactly where your assets are. Real estate is another example. The tax systems of the local communities want to know, for example, who is building and where. Nobody can escape taxation now, because through this kind of surveillance, everybody knows if you build, for example, a balcony onto your apartment, building or house – the satellite will catch it. Real estate forestry, forestry management, coastline erosion, shifting climate patterns, urban planning, anything you want can be picked up by the satellite cameras. It is an incredible source of information that can change any number of public service industries.

Satellite surveillance is an on-demand service. It is a new industry and does, however, involve risks. A company that puts 1,000 satellites into space is looking at investments of about $30,000 to $40,000 per satellite, not including the costs of the launch, or anything else, just the piece of equipment that is going up there. How do you ensure an investment of many millions of dollars for a satellite constellation in space? There is thus a need for insurance. If, for example, your satellite constellation has a lifetime of two years, and it gets struck by debris, then at least you have paid a certain fraction for insurance in order to be protected. How does the insurance business work here? How do you check, on demand, that the constellation is in normal condition? Who wants to know that the constellation is in normal condition? The owner wants to know, but so does the insurance company.

The problem is that there are huge obstacles to providing reliable and accurate LEO surveillance services on demand. The most difficult part is providing the radar surveillance. The system works by sending radar energy into the sky for tracking and imaging, if possible, the constellation of satellites. The most expensive part is the high-power, ground-based radar illumination. That means that, on the ground, you must have a strong enough radar source of energy that is capable of being aimed at the right place in space, providing enough illumination going up there and then a sufficient amount of energy coming back, so that you can collect it and create an image and provide information. It is very expensive. The biggest radar source of energy on the ground in the United States was built in the 1970s and is located north of Los Angeles in the Mojave Desert. It is a 70-meter parabolic dish that works both at the X band, meaning at a wavelength of 3 centimeters, and also at the S band, which is about 12 centimeters. This dish – called the Goldstone Antenna – provides energy that is strong enough to reach deep space; it can track satellites that are going out of the Earth's orbit into deep space. It was this dish, for example, that tracked the errant satellite believed to be carrying toxic material back in 2008. It is the only big antenna in the United States, and it is extremely expensive. In recent years, I have been told that it has been failing a lot, because it is aging. There are thus great obstacles and an incredible amount of money needed.

The surveillance market of the low Earth orbit

Who provides Low Earth Orbit surveillance services on demand? There is only one company that does that today; it was created in 2016. How does it provide LEO radar surveillance? It made a smart business decision: the company realized that it could never build a high-frequency, high-power radar source on the ground, so it rents the dish antenna, the Goldstone Antenna, to clients who want to probe certain parts of space. Up until now, the illumination from the ground to the sky was 100 per cent controlled by the government, whether it was primarily NASA or to a complementary extent the US Air Force; this information is all US-centric. I believe there is a radar system in France, situated somewhere in the north. There are some smaller ones that are operated by MIT Lincoln Labs in Lexington, Massachusetts, an organization developed primarily to carry out entering missile surveillance. We know that they have very advanced techniques and are doing very intelligent things, but their ground sources cannot be used.

NASA, about a year or so ago, realized that this situation was untenable. In response, a group of NASA scientists proposed decentralizing the system by using on the ground multiple small 5-meter antennas that are coordinated to send energy up into the sky rather than using one big 70-meter antenna. This project was announced at the meeting of space scientists in Maui in September 2017. By Christmas, the government had declined the project proposal. I asked myself, why did the government turn down this option? It is not quite rational. Why doesn't the government want to decentralize and create technologies that are relatively inexpensive? The government could buy several 5-meter dish antennas at a much lower cost than building another 70-meter antenna. But what did they do? They decided to build a second 70-meter or so dish antenna. The economics of the government's deployment of resources is not rational here. This situation is happening right now; it was not 20 years ago. It is occurring at a time when the US government is very private-enterprise oriented and conscious of how it is spending resources, and so on. It is thus of the utmost importance at this moment in time for private enterprise to enter into this domain. Private enterprise can provide a certain amount of sensible thought and decision making to all this.

Once government funding is gone, then cost and efficiency matter and must be calculated carefully. That is a provocative declaration. In other words, as long as the government is involved, cost and efficiency do not seem to matter. If the government is going to do something, the cost is irrelevant, because everybody is paying for it, so it is as if nobody is paying for it. Such thinking and behavior has to change. It is all about tools for risk assessment, and perhaps most important are space surveillance tools that provide diverse information. What we really need to do is to provide for risk assessment. Space surveillance tells us exactly what is happening in space, so that we can assess all sorts of risk: who is going to collide with whom, which objects are moving in the correct trajectory, and so on.

New risks, new techniques for assessing debris

With mathematician and fellow researcher Josselin Garnier, we have been working on a project involving drone-based receivers to improve the risk assessment of debris, as shown in Figure 2 below, which gives the schematic of the proposed setup. If a satellite is in space at an elevation of about 500 kilometers, represented by the green arrow at the top of the schematic, it is moving at a velocity (VT) of about 7.6 kilometers per second. There is one source on the ground that is beaming radar energy in several possible frequency ranges. R1, R2, R3, and so on, as shown in the figure, are the drones that are carrying the passive receivers that record the reflected signals. They are at an elevation of about 20 kilometers above the Earth. That puts

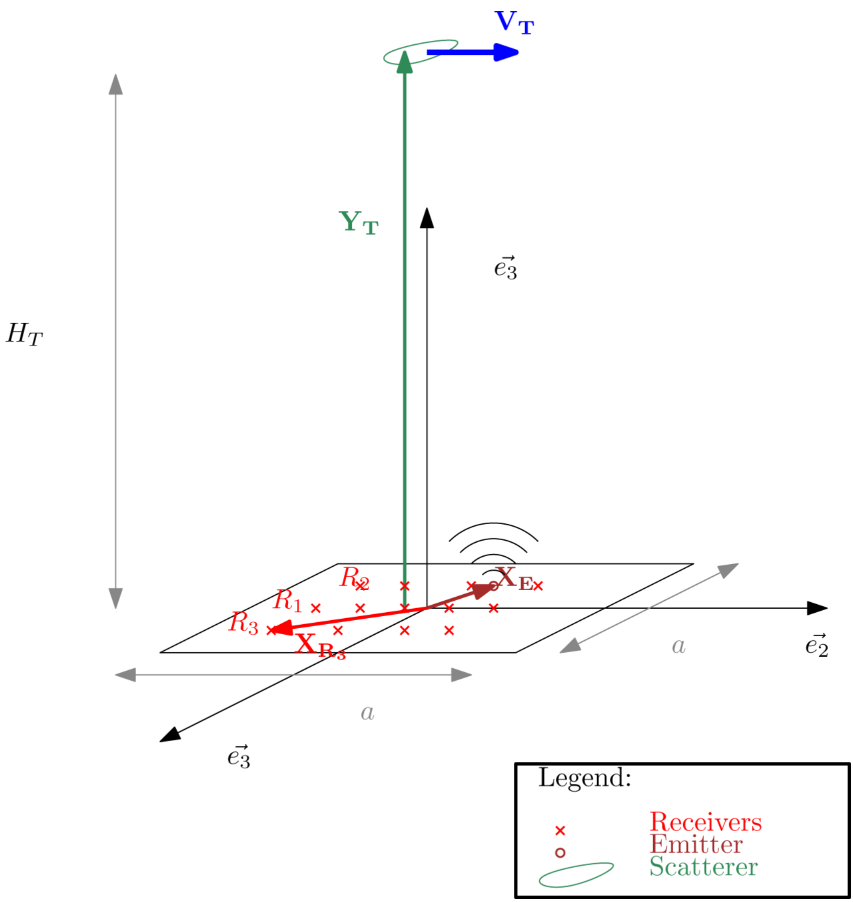

Figure 2: Schematic of drone-based receivers, asynchronous and distributed ground-based radar illumination, and the use of correlation-based imaging.

them roughly above the tropopause, in other words, going upward from the surface (tropopause is the point where air ceases to cool with height, and becomes almost completely dry). At 20 kilometers or more above the atmosphere, what is above you is mostly empty, and there is no atmospheric distortion for even high frequency radar. The object creating this energy is likely to be a dish antenna that is, say, 5 meters, and thus too big to fit on a plane. The energy is going up and then much less energy is reflected back, because the energy reflected from an object of 1 centimeter is tiny.

That energy coming back is collected by the receivers on the drones. Importantly, if this information – the reflected energy that is coming back from these objects – has to go through the atmosphere, it will get distorted. It will not get distorted, however, if the wavelength is relatively long, say 10 centimeters thereabouts or more. At that wavelength the atmosphere will no longer matter. If, however, the wavelength is down to 1 centimeter, at 30 gigahertz, or 3 millimeters, those are good frequencies for resolution. A lot of companies and the government want to use the new W-band, which is 3 millimeters. If it is in that regime, then the atmosphere matters, and it is thus important to put the drones there.

We started this project in 2013. Josselin and I wrote the book *Passive Imaging with Ambient Noise*, published by Cambridge University Press in 2016,[3] and then we wrote a paper with Fournier and Tsogka,[4] published in 2017, in which we analysed the resolution of this system in detail, showing that the resolution of the system is really quite good. Correlation-based imaging has been shown to be more robust to medium fluctuations, such as atmospheric lensing and aberrations.[5] This would be true for receivers that are not located on the ground but are flying above the turbulent atmosphere. Indeed, considering airborne receivers transforms the passive correlation-based problem to a virtual source array imaging problem that has been studied for stationary receiver arrays in [3]. The key idea is that passive correlation-based imaging becomes equivalent to having a virtual active array at the location of the passive receivers. By moving the receivers above the turbulent atmosphere, the atmospheric fluctuation effects on imaging are minimized and the imaging resolution appears as if we were in a homogeneous, fluctuation-free medium. Correlation-based imaging is passive, because it can be carried out using opportunistic, unknown emitters. In the imaging setting considered in our publications, opportunistic sources could be even global navigation satellite systems. Our resolution estimates suggest that the moving object can be localized with very high accuracy, of the order of the wavelength of the imaging system. Our analytical resolution estimates are validated with detailed numerical simulations. Moreover, our numerical results suggest that around 10 receivers are sufficient for making the theoretical resolution estimates with an aperture diameter of about 400 kilometers. This empirical rule of the order of 10 receivers is furthermore shown to be correct theoretically when considering a regular grid of receivers, both for the matched-filter and the correlation-based imaging method. The US government has asked us to try to go further with this project, so now instead of doing pure science, we must do something that is a little bit more directed in order to obtain results that are more focused.

The aim of the project is to study the limits of low-power, ground-based illumination, in other words, how much energy do we need? We think that the energy should be distributed, that there should be a farm of sources on the ground – say 100 radar sources – placed into an area of about 100 square kilometers. Those sources are beaming up energy, which is not quite coordinated, because that would be expensive. The sources are relatively inexpensive, and the question is, how much energy do we need to send up to illuminate an area in space at 500 kilometers' elevation? How much energy do we need to illuminate an area of say 200 square kilometers up in space, in order to see centimeter-sized objects? That is a calculation that has to be done carefully. We know how to do it; we have done it. We have realized with Josselin that in the various papers that we have written over the last 15 years or so, just about every technical question we need for this project can be found in these papers.

Our job now is to collect the information correctly from those papers and put it into place in order to create a credible narrative for this project. We want to study the effects of the atmosphere in the W-band – the 3-millimeter wavelength – that is, especially at higher frequencies. It is very important to go to high frequencies, because it keeps the equipment small: the receivers are small enough to be put on very small drones. The drones exist; they are flying at an elevation of 15 to 20 kilometers. Everything exists; everything is out there. The only thing that does not exist today is relatively high power sources at a 3-millimeter wavelength. That technology has not yet been developed, because there was no real need for it for many years. The private sector is now building 3-millimeter wavelength radar sources for private use. For example, there are now similar small radar devices that are being used for collision avoidance in cars. You put the device on your car, and it can be used to transmit a radar signal at 30-50 meters. This is a new, very intelligent radar source that has come out in the last few years. It is a wonderful technology and will likely revolutionize collision avoidance for self-driving cars. This is all moving in the right direction, but for now the devices are too low powered: a 30-50-meter range means nothing in the context of space surveillance. We would like the energy to go to an elevation of 500 kilometers….

Our original objective was to provide resolution for debris in space. If an object is there, can we get a radar picture of the object that is on a scale of a few centimeters? That is just one objective, and, theoretically, I believe that we can do that. We are working in that direction with a small company that will take measurements. But what we really want to do is to study the possibility of imaging simultaneously and in detail large clusters of debris, containing hundreds or even thousands of objects, and coordinate the imaging information over an area of about 200 to 400 square kilometers in the sky. That is our current challenge.

Endnotes

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George Papanicolaou is a Professor at Stanford University, holding the Robert Grimmett chair in mathematics since 1997. He is also a member of the American Academy of Arts and Sciences, the US National Academy of Sciences, the Society for Industrial and Applied Mathematics and the American Mathematical Society. He has been awarded the ICIAM Lagrange Prize for 2019. The invited plenary speaker at the International Congress of Mathematicians in 1998, he also received a Doctor Honoris Causa from the University of Paris VII in 2011, was the recipient of the William Benter Prize in Applied Mathematics in 2010 and the SIAM John von Neumann Prize in 2006. George Papanicolaou is the author of several books and over 200 journal articles.

His main research interests include electromagnetic wave propagation and diffusion in random media and mathematical analysis of multi-scale phenomena; scattering effects in imaging and communication systems, including time reversal arrays and the use of optimization methods in imaging. In financial mathematics, his research focuses on the use of asymptotics for stochastic equations in analysing complex models of financial markets and in data analysis and modeling and analysis of systemic effects in multi-agent systems and interacting markets.

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