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Twinkle, Twinkle, Little Star

The title of this editorial is borrowed from a popular children's lullaby from the 1800s, which reads "Twinkle, twinkle, little star, how I wonder what you are!" It reminds me of the vast expanse of unexplored space (and science) that lie before us.

The human race has always been fascinated by space—and who would not be? Its shining stars continually challenge us to get closer and unravel their mysteries. Civilizations old and new have been defined by their relationship with space and by their contribution to astronomy.

This past August, NASA launched its first mission to explore a star. It will travel for six long years and explore the atmosphere of the sun at a safe distance of almost 4 million miles. Another Japanese spacecraft, with rovers built in cooperation with German and French space centers, will be exploring the surface of a 1-km-wide asteroid after traveling for more than three years. Earlier, in 2003 and 2011, NASA launched the rovers Spirit, Opportunity, and Curiosity to explore areas on the surface of the planet Mars. These efforts are fantastic examples of creative feats of engineering. Imagine flying robotic machines into far-away planets or asteroids in dark space, landing them on predetermined spots, and controlling them remotely. Significant ingenuity drives these accomplishments.

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Our scientific community should be proud of these achievements. It is not a secret that signal processing theory and methods have been deeply entrenched in space exploration since its early days, providing powerful tools for collecting, transmitting, and processing data. The least-squares method itself, and its famous recursive version, are the outcome of a data fitting exercise by Gauss in 1795 while trying to predict the location of the comet Ceres from past rudimentary telescope measurements. More recently, in a lecture given by the French mathematician Yves Meyer (of wavelets fame) at EPFL in Switzerland in September 2017, the speaker's opening statement was to show how "signal processing has played a role in the detection of gravitational waves!"

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The observation of these waves is considered one of the most important discoveries of recent times [1]. For the uninformed reader, the existence of gravitational waves, which amount to invisible ripples in the space–time fabric, was predicted in the early 1900s, but their detection has remained elusive for more than a century until their discovery in February 2016. It is no wonder that three of the scientists involved in the discovery were awarded the 2017 Nobel Prize in Physics almost instantly. The gravitational waves they detected resulted from the collision of two black holes a mere 1.3 billion years ago! Space exploration at this level has often enabled the discovery, testing, and validation of deep scientific theories including Einstein's theory on how planets and stars distort space and time. Experimental validation of scientific theories is a precious exercise because it tests our hypotheses, deepens our understanding, and propels us to explore more confidently. Space exploration has also led to many technological advances that have benefited humanity right here on Earth.

Still, and oddly enough, we have been shamefully less successful at exploring our own planet Earth. According to the National Ocean Service of the U.S. Department of Commerce [2], oceans cover 70% of the surface of our planet, and yet about 80% of them remain unexplored and their floors largely unmapped to accurate measures. Stated another way, we are ignorant about half of the planet on which we live! Imagine if all the water covering our oceans and seas were to disappear, what would you get? You would be left with vast expanses of land. If you were to drive your car through this wilderness, you will be on your own for almost half of the earth's surface; no online maps would be available to guide you!

There are, of course, many reasons why we have not explored our oceans

more vigorously. Besides the extreme environment that one encounters as we move deeper into the oceans, and the more limited resources available for ocean exploration, humans appear to have a natural fascination for space exploration. Just observe how some of the most successful entrepreneurs of our times have marched almost by inertia toward commercial enterprises to explore spaceflight opportunities. These include, according to data from *Wikipedia*, companies such as Blue Origin founded in 2000 by Jeff Bezos (of Amazon), SpaceX founded in 2002 by Elon Musk (of Tesla), and Virgin Galactic founded in 2004 by Richard Branson (of Virgin Group). To a lesser degree, some entrepreneurs have ventured into exploring the deep sea, including the impressive 2012 Deep Sea Challenger submersible of Canadian filmmaker James Cameron (of the *Titanic* film), and the Schmidt Ocean Institute founded in 2009 by the former Google chairman Erich Schmidt.

That said, whether in space or on our planet, we readily identify a frontier calling out for attention. There is a clear need for the development of more science, technology, and methods for the exploration of extreme environments. Signal processing scientists can and will play an important role in enabling these developments. Why? Because, by training, we are experts at drawing inferences about unobservable variables from indirect measurements. There are many success stories, including scattering methods for detecting layer boundaries in geophysics or oil exploration applications, and noninvasive imaging techniques such as MRIs for biomedical applications, and sonar technology. In fact, this latter technology is already one of the main techniques used to map the ocean floor up to 100 meter resolution. However, only 10% of the oceans' floors have been mapped by the technology and the mapping that exists for the remaining surface has a poor resolution in the order of 5 km [3]. With this state of affairs, one can better understand why it has been such a daunting task to locate the aircraft of Malaysia Airlines flight 370, which tragically disappeared back in March 2014. Imagine how much discovery is awaiting us in the unexplored oceans: new materials, precious metals or minerals that may have gone undiscovered, species with wondrous biomechanisms that may motivate new technologies, and even undiscovered substances that may lead to new medical treatments.

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These facts are humbling. We pride ourselves on the technological advances of the 21st century, such as the ability to track (whether legal or not, right or wrong) every online click and every cell phone user, and yet we still cannot locate a missing aircraft! Even more humbling, there is so much we do not know right here on Earth. I am always amazed at the discovery of new species. We are desperately looking for the tiniest forms of life on remote planets, and yet we continue to be ignorant of the full biodiversity that encircles us. According to [4], it is estimated that 18,000 new species are named every year. And we are not talking about tiny species. In 2018, a new species of the great apes was discovered called the *Pongo Tapanuliensis* orangutan (only 800 of them are left in the Indonesian island of Sumatra). According to the United Nations Environmental Programme [5], it is believed that about 150–200 species become extinct every day. How many of these extinct species belong to a group that we may not have discovered yet?

Even while working on this column, it was announced on CNN's website in August 2018 that a "Never before seen Amazon tribe" has been spotted on drone video. Isn't that astonishing? We are referring to spotting unseen human beings, like you and me, on planet Earth in 2018! The indigenous people spotted in this video live in a large protected area in the Javari Valley in Brazil. Almost a week later, the same CNN website announced the discovery of an 85-mile long deep-sea coral reef off the east coast of the United States; one of the most technologically advanced nations on Earth! All of this was hiding in plain sight.

You can now understand why I feel frustrated and surprised when someone asks, "what else is there to do?" Their argument is that we live in the 21st century and our "advanced" civilization has attained so much sophistication in its technology from the online revolution, to intelligent machines, to deep space exploration, that there is not much more to discover. Some use this argument broadly referring to science in general, and others are more specific and target our signal processing discipline. Luckily enough, there is so much we do not know and may not even come to understand fully. There are so many unanswered questions, and so much opportunity for new methods in science, including in signal and information processing, that the path forward is limitless. We

have only explored the tiniest fraction of space and a fraction of planet Earth. Not to mention many other areas of exploration in biology, basic and natural sciences, social sciences, and so forth.

Discovery never ends. The uninformed sees an obstacle where there is a wall. The scientist wants to see through the wall or jump over it. This is also true at a more abstract level. I would assume that many of you have shared a similar experience with me. When I derive a new result, I often sit back in awe wondering at how "the more we learn, the less we actually know!" In other words, similar to how this new result was hiding in some invisible space waiting for someone to discover it, many more discoveries are awaiting their chance to be brought forward for all of us to admire. How many more unknowns are there? Enough to keep our curious minds busy for ages.

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The human race has always been fascinated by exploration including in many literary works. Jules Verne's 1870 classic *Twenty Thousand Leagues Under the Sea* chronicled the adventures of a fictional submarine and its exploration of the world's oceans. Interestingly, his book was preceded by Verne's 1864 earlier classic *Journey to the Center of the Earth*. That is another frontier yet to be explored. Exploration and discovery will never end. For as long as we look up into the skies, we will continue to wonder at the twinkling stars and the mysteries that lie beyond them.

Once, two new graduate students walked into my office showing interest in joining my research team. One student had just completed his undergraduate studies while the second student had completed his master-level studies. I printed a research article and asked them to return in a week to present it to me. The undergraduate student was understandably concerned that the other student is better prepared to read the article given his more advanced studies. I assured them that my criterion to judge their presentations would be different. The undergraduate student would need to convince me that he understood what *was* written in the paper, while the master student would need to convince me that he understood what *was not* written in the paper (such as discussing any assumptions or approximations that could be relaxed or are limiting). The students were expected to approach and critique the paper from different perspectives. Even here, in this simple exercise of reading a paper, one can find opportunities to push knowledge and discovery further.

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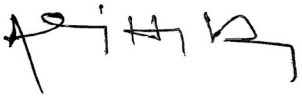

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