Sol Golomb and a twice-in-a-lifetime celestial event

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When I was a high school student in the United Kingdom in the 1980s, one of my teachers generously ran a mathematics enrichment club for enthusiasts. In one of these sessions, he fascinated us with the topic of polyominoes [1], a rich source of geometric puzzles that is nowadays recognised as the inspiration for the wildly popular video game Tetris. The first time I can recall hearing the name Solomon Golomb was when I asked the teacher: who proposed the concept of polyominoes?

Some thirty years later, it was my honour to be the co-chair with Tor Helleseth of the Technical Program Committee for the 2012 SETA (SEquences and Their Applications) conference at the University of Waterloo [2]. By this time I had met Sol in person several times at conferences, and knew that he was a legendary figure in information theory and discrete mathematics. Guang Gong, the conference local organiser, proposed holding the conference in early June in order to coincide with Sol's 80th birthday. Tor and I readily agreed, and set aside 5 June for a full-day special session of the conference in his honour, followed by an evening banquet celebration. When we heard that Sol had been awarded the 2012 Proctor Prize of the Sigma Xi Scientific Research Society, we invited the director of the society to present Sol with the prize at the banquet. The day of 5 June 2012 was shaping up to be memorable, but I didn't yet realize there was another delight awaiting us.

Five weeks before the conference, Alex Pott emailed me from Germany: "Do you know that SETA is a venus transit conference? Well done! It is easier to watch in Waterloo than in Germany." I have to say that I had no idea what Alex was talking about! After some online browsing, I discovered that a transit of Venus occurs when the planet Venus passes directly between the Sun and Earth. It is similar to a solar eclipse of the Moon, but differs in two important ways. Firstly, because Venus is much further away from Earth than the Moon is, it cannot obscure the entire disc of the Sun but instead appears as a tiny black dot moving across the Sun's surface. Secondly, a transit of Venus is extremely rare, occurring only twice within eight years and then not again for more than a century. The previous transit had occurred in June 2004, and the next one was due on 5 June 2012: the very day we had dedicated to Sol's 80th birthday celebration! This really was a twice-in-a-lifetime celestial event: the next transit will not occur until December 2117, so although we knew that the conference participants might one day attend another SETA conference, they surely would never again have the opportunity to witness a transit of Venus.

We therefore adjusted the conference schedule to incorporate an observation of the transit of Venus. I found out that the local branch of the Royal Astronomical Society of Canada[3] was holding a "star party" on the campus of the University of Waterloo, and their representative graciously told me we were all welcome to drop by to view the transit through large telescopes on the evening of 5 June. We provided each conference attendee with a pair of viewing goggles so that they could observe the transit safely just before the start of the banquet.

I had learned that transits of Venus were historically important for estimating the Astronomical Unit (the average distance between the Earth and the Sun) using the principle of parallax to combine information from observations of the transit made from different points on the Earth's surface. In fact, Captain James Cook's first voyage was to Tahiti, in order to observe the 1769 transit. A marvellous poster[4] gave this colourful background:

> Much of the mystique of the ToVs [transits of Venus] stems from the incredible stories of observers' astronomical endurance and fortitude. Le Gentil missed one ToV and hung around the far east for another 8 yrs. to see the next, only he couldn't (clouded out; and people at home thought he had perished — perhaps he wished he had). Chappe d'Auteroche successfully observed his ToV, but died from yellow fever almost immediately afterwards (saving the trouble of a return journey). Mason & Dixon's expedition got beat-up by unfriendly cannonballs, Winthrop was harried by Newfoundland's finest insects, and Nevil Maskelyne before he got home had to make his way through a lot of expensive drink (doubtless assuaging the hurt — he too was cheated by cloud).

On the first day of the conference, we played a five-minute NASA educational video[5] to provide some basic scientific and historical context for the following day's transit viewing. Afterwards Sol came up to me and, with a gleam in his eye, said "I actually know a little about Venus". I suspected this actually meant that Sol knew considerably more than "a little", and asked him to elaborate. Without hesitation, Sol began to recount historical events and technical details from fifty years earlier as if they had happened the previous week. After listening to his answer with increasing excitement, I arranged a special speaking slot shortly before our transit viewing for Sol to repeat what he had told me to all the conference attendees.

Here is the riveting story Sol told us (supplemented by documents and personal recollections he later kindly sent me). In 1962, the NASA space probe Mariner 2 became the first spacecraft to send back information from another planet, passing within 21,000 miles of Venus after a journey of 36 million miles from Earth. The key to successfully directing the probe to reach the vicinity of Venus was having a highly accurate estimate for the distance from Earth to Venus (or, equivalently, for the Astronomical Unit). The problem for the space probe designers was that previous estimates of the Astronomical Unit, based on the two 19th century observations of the transit of Venus, were actually in error by one part in a thousand. If Mariner 2 had depended on these estimates, it would not have come remotely close to observing Venus. But by the time Mariner 2 was launched, the error in the estimate of the distance to Venus had been reduced to less than one part in a million! How was this critical improvement achieved?

In 1961, a team at NASA's Jet Propulsion Laboratory (JPL) used a radar signal to measure the distance between the Earth and Venus with enormous accuracy. This was the first successful radar contact with another planet of the Solar System. The team determined the distance by measuring the time for a radar signal transmitted from Earth to be reflected from Venus and detected back on Earth. Sol was the project manager of the Venus radar project at JPL, and had already conducted pioneering investigations into linear feedback shift register sequences (having the 2-level-autocorrelation property) that he would later present in his classic book[6]. In a critical insight, Sol realised how to combine many such sequences advantageously. In Sol's words[7]:

> the "ranging system" I designed at JPL combined a number of much shorter 2-level-autocorrelation sequences of relatively prime periods, using a Boolean function such as the "maximum decision" function on an odd number of inputs, which is positively correlated

> with each individual input . . . The result was a random-looking binary sequence of sufficiently long period that its "gross ambiguity" would exceed the diameter of the solar system!; but because it was positively correlated with each of the component subsequences, our correlation (over hours at a time) was sensitive enough to determine "where we were" in each of the subsequences, and this information was combined, using the Chinese Remainder Theorem, to specify where we were in the overall system . . . The details of my JPL ranging system were described in several JPL reports, but (to my subsequent regret) were never published in journal or book form. However, the above description summarizes the mathematics of it. I had some very talented engineers working for me to reduce everything to hardware that worked.

I still marvel at the amazing coincidences that unfolded during the week of the SETA 2012 conference. Not only had the organisers unknowingly fixed the conference schedule to include the last day in more than a century that would include a major astronomical event involving the planet Venus; but our guest of honour turned out to have played a pivotal role in combining discrete mathematics with communications engineering five decades earlier to determine the position of this celestial body with unprecedented accuracy. Thank you, Sol!

References

1. S. W. Golomb, *Polyominoes: The Fascinating New Recreation in Mathematics* (Charles Scribner's Sons, New York, 1965).
2. SEquences and Their Applications (SETA 2012), University of Waterloo, ON, 4–8 June 2012 (`http://seta2012.uwaterloo.ca`).
3. Kitchener-Waterloo Centre, The Royal Astronomical Society of Canada (`http://www.kw.rasc.ca/`).
4. R. A. Rosenfeld, Transit of Venus 2012 June 5, Poster.
5. The Transit of Venus Part One (2012), `https://sunearthday.nasa.gov/2012/materials/transit1.m4v`.
6. S. W. Golomb, *Shift Register Sequences* (Holden-Day, Inc., San Francisco, CA, 1967).
7. S. W. Golomb, Personal communication, 17 April 2013.

Fig. 1. Sol Golomb observing the transit of Venus, 5 June 2012 (photo courtesy of Kelly Boothby)

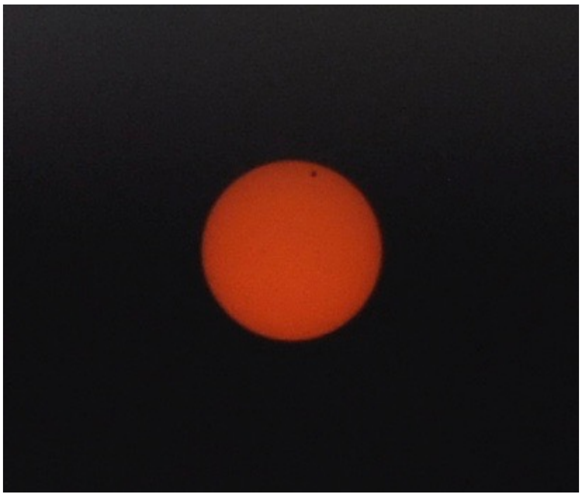

Fig. 2. The transit of Venus observed from Waterloo, Ontario, 5 June 2012 (photo courtesy of Krystal Guo)