The Challenge for 2050: Cohesive Analysis of More Than One Hundred Years of Planetary Data.

M. P. Milazzo, L. Kestay, C. Dundas; U.S. Geological Survey, Astrogeology Science Center, 2255 N. Gemini Dr., Flagstaff, AZ, 86001 (moses@usgs.gov)

Introduction

The year 2050 will mark 106 years since humans opened the door to space and to the Solar System. In 1944, *MW 18014*, a German V-2 rocket was vertically launched and became—with an apoapsis of 176-kilometers—the first human-made object to reach space. Near-space and just beyond continued to be explored over the next decade and a half. In 1957, of course, Sputnik 1 became the first artificial object to achieve Earth orbit [1]. Robotic exploration of the Solar System began when *Luna 1* was launched from Tyuratam, U.S.S.R. on January 2 1959. Its intended scientific goals included measurements of interplanetary gases, corpuscular radiation of the Sun, and magnetic fields of both Earth and the Moon. *Luna 1's* instrument suite included a magnetometer, geiger counter, scintillation counter, micrometeorite detector and other instruments. *Luna 1* discovered the solar wind and that the Moon has no magnetic field [1].

Now, 58 years after our first step into interplanetary space, human-built, robotic exploration of the Solar System has expanded to visit every planet, dwarf planets, and several small Solar System bodies. We have repeatedly sent spacecraft to the Moon and to Mars. The robotic explorers *Pioneers 10* and *11*, *Voyagers 1* and *2*, *Galileo*, and most recently *Juno* have visited Jupiter. Saturn, too, has been visited by multiple spacecraft, most recently the incomparable *Cassini* mission. We have sent flyby missions and followed up with orbital missions to Mercury, Venus, the Moon, and Mars. We have landed and operated robots on the surface of the Moon, Venus, Mars, Titan, comets, and asteroids. We have commanded robots (or will shortly command, in the case of Cassini) to enter the atmospheres of the two largest planetary bodies in our Solar System [1].

Over these 58 years of Solar System exploration, there have been more than two hundred launch attempts of crewed and robotic spacecraft intended to Explore the Solar System beyond Earth. There have been 63 fully-successful and currently-operational missions to the Moon and 22 to Mars [1] (Fig. 1).

Each of these missions has returned or is continuing to return increasingly large volumes of scientifically valuable data from increasingly complex and innovative instruments. The challenge we face today, is how to combine scientific data from earlier missions gathered with older technologies with new data from new kinds of instruments on new spacecraft. This challenge is expected to become even more formidable as more data from new instruments on new spacecraft accumulate over the next 33 years.

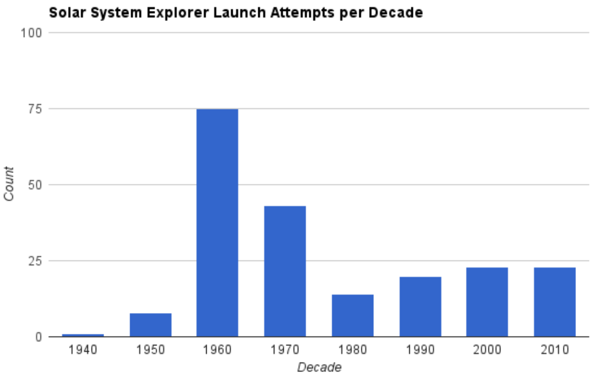

Figure 1: *Plot of the attempted and successful launches of spacecraft used to explore the Solar System. The large number of attempts in the 1960s is probably an artifact of the Space Race between the U.S.A. and U.S.S.R. Plot generated from data compiled from NASA mission websites and timelines.*

Analysis of Large, Multi-Instrument, Multi-Spacecraft, and Temporally-Disjointed Data Sets

By 2050, we will have accumulated nearly one hundred years of spacecraft observations of the Solar System. Many of the data acquisition techniques we are developing today will, by then, be standard operations. New techniques we haven't considered will be pushing the boundaries of what we only dream to be possible today.

Laser ranging provides one illustrative example. This form of remote sensing was first applied to planetary studies in 1969 with the Laser Ranging Retroreflector Experiment on Apollo [2, 3]. Since then steadily more sophisticated laser altimeters and LiDAR devices have been utilized on planetary missions. However, even nearly five decades since the first use of this technology, techniques for combining laser altimetry with stereo-imaging-derived topography are still lacking in planetary science. Such methods are only now being developed and tested for robustness and accuracy on the

Earth and there will be significant challenges to applying these methods to the sparser data available from planetary missions. This lag between the development of a new observational technology and the ability to integrate the new observations with other data sets is likely to be a continuing significant issue as we move toward smaller, more science-question-specific instrumentation. We can work today to limit this lag by planning and developing data fusion and analysis tools and techniques alongside the development of new instrumentation and before and during the planning of spacecraft missions. By 2050 we also expect planetary missions to be using new techniques to probe below the surface that we do not use (much) now. One critical difference will be the ability to look in five dimensions (x,y,z,t, and wavelength) as opposed to two or three today. Being able to work in five dimensions will require fundamentally new tools. Additionally, combining data from fundamentally different data types will be critical. One possible example is the combination of seismograms, sounding radar, Laser Induced Breakdown Spectroscopy (LIBS) spectra, drill core data, and a fifty-plus-year time-series from visible to thermal IR imaging to study the Martian surface.

One key result of recent missions is that even bodies we considered as frozen relicts of the early solar system have ongoing active processes. Past and current missions have revealed surface changes such as slope processes and dune movement on Mars, volcanic eruptions on Io, rainfall-induced (and other) changes on Titan, and new impact craters on the Moon and Mars, as well as weather on Mars, Titan, Venus, and the giant planets. Future missions with higher-spatial- and -temporal-resolution and/or a longer time baseline will improve on these records and could detect additional types of change, such as active volcanic flows on Venus, additional changes on Titan, or plume deposits on various icy worlds. As we accumulate longer records of higher-spatial-resolution data, we will be able to measure the effects of these changes and understand their causes, unlocking the diverse processes active today. We suggest that many of the key scientific breakthroughs in 2050 will focus on understanding these active processes or require a thorough understanding of the ongoing processes in order to extract information about the deeper past. These prospects point to some essential efforts needed to prepare for planetary science in 2050. First, we must develop the tools to co-analyze highly disparate data. Second, we must maintain existing data to ensure that it can effectively be combined with new observations within those tools.

The new tools must go beyond simply overlaying diverse data in a display (though even this is a challenge given the five or more dimensions to the data collections). These tools must call the attention of the researcher to the key quantities that are significant for better understanding specific processes at a specific location. Highlighting areas that have changed with time is a simple example of this concept. Another key characteristic of the new tools is that they must promote and support collaboration between a number of specialists because no one person will be able to know the intricacies of all the disparate data sets. While current research into techniques such as data mining and remote collaborations will undoubtedly be useful, it is important to focus on the role of the human brain in recognizing and solving novel scientific problem. Some aspects of this include (1) automating rote processes that numb the brain, (2) providing statistically robust assistance in distinguishing real anomalies from noise, and (3) presentation of data in physically meaningful units with uncertainties that can be readily perceived. For example, searching for temporal changes will require better tools to automatically process and compare data. For visual imagery, this requires separating the effects of real surface changes from those due to different lighting and viewing geometry as well as camera characteristics such as resolution and signal-to-noise ratio.

> We must maintain existing data in such a manner as to ensure that it can effectively be combined with future observations.

As importantly as having scientific tools to combine new data types, we must also maintain the utility of old data. For example, science is still being accomplished using *Mariner 10* data from its flyby of Mercury in 1973. These data have been reanalyzed in light of new data from the MESSENGER mission [4]. *Viking* data from Mars are being combined with recent observations to understand eolian changes [5]. And our modern data sets, too, will be considered ”old data” by 2050, but will still have great potential to advance science.

References

[1] NASA. *Nasa: https://www.nasa.gov/.* [2] Faller, J, Winer, I, Carrion, W, et al. (1969), *Science*, 166:99–102. [3] Murphy, T, Adelberger, E, Battat, J, et al. (2010), *Icarus*, 208:31–35. [4] Wilkinson, J. *The Solar System in Close-Up*, pp. 69–83. Springer (2016). [5] Geissler, PE (2005), *Journal of Geophysical Research (Planets)*, 110.