Kepler Mission Development Challenges and Early Results

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Abstract—Kepler is NASA`s first mission capable of detecting Earth-size planets orbiting in the habitable zone of stars other than the sun. Kepler comprises a space telescope designed to continuously monitor the brightnesses of more than 100,000 target stars, and a ground segment to analyze the measured stellar light curves and detect the signatures of orbiting planets. In order to detect Earth-size planets orbiting Sun-like stars Kepler was designed to provide unprecedented photometric sensitivity and stability. This paper addresses some of the technical challenges encountered during the development of the Kepler mission and the measures taken to overcome them. Early scientific results are summarized.

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1. INTRODUCTION

Speculation about habitable worlds orbiting other stars is at least as old as the ancient Greeks. NASA's Kepler mission will at long last answer the question of how frequently planets of various sizes and orbits are to be found circling stars in our Galaxy, with an emphasis on terrestrial planets orbiting in the habitable zones of stars like our Sun. The habitable zone is that distance from a star where the equilibrium temperature of the planet would permit the existence of liquid water, believed necessary for any form of life we might recognize. Detecting the presence of an Earth-size planet orbiting a Sun-like star is extremely difficult because the planet is so much smaller and less massive than its star, not to mention millions of times less bright. The approach taken by Kepler is to detect the passage of a planet across the disk of its star by measuring the slight drop in brightness caused by the planet blocking some of the star's light as it passes in front of the star. The passage of a planet across the disk of a star is called a "transit."

For there to be a transit the geometry must cooperate such that the Earth lies nearly in the planet's orbital plane. Assuming that planetary systems are oriented randomly, the likelihood of any planetary orbit being adequately aligned is only about 0.5%, so the vast majority of stars will not exhibit transits. To perform a statistically significant survey, and to have a meaningful null result in the event no transits are detected, the number of stars to be monitored must be quite large. Because it is not known when the transits will occur it is also necessary to monitor the stars simultaneously and continuously. Since transits occur once per orbit, the time interval between transits provides the planet's orbital period. By measuring the relative drop in the star's brightness resulting from the transit, and by knowing the star's size and mass (something astronomers can determine by various techniques) the diameter of the planet and its orbital radius can be determined, and its temperature inferred.

Statistical arguments determine that the survey should include at least 100,000 stars; in fact, Kepler began with more than 150,000 stars, carefully selected to be the most Sun-like. To support continuous monitoring, a single region of the galaxy rich in stars was selected between the constellations Cygnus and Lyra, an area sufficiently out of the ecliptic plane that the Sun does not preclude its being observed year round by a spacecraft. The field of view required to encompass 100,000 stars of suitable type and brightness, even in this star-rich region, is about 100 square degrees, and the plate scale necessary to image and measure individual stars requires a very large focal plane, on the order of 95 megapixels. Because the galaxy is filled with eclipsing binary stars and other phenomena that can mimic planetary transits, false positive detections will be common and methods are needed to identify and reject them. One such method is to measure multiple transits, and assure that the time interval between them is constant to a high degree of precision. Earth orbits the Sun once per year; detecting several transits of an Earth-Sun analog therefore requires a mission life of several years.

Then there is the question of measurement sensitivity and precision. Given the limiting magnitude of stars in the survey and the number of photons required to achieve an adequate signal to noise ratio, the telescope must be of about 1-meter aperture. If our solar system were observed from another star, the transit of the Earth across the disk of the Sun would result in a drop in brightness of approximately 80 parts per million (ppm) for about 13 hours. To have a secure measurement of transits of this depth and slightly smaller, Kepler's photometric sensitivity was set at 20 ppm.

Nothing like this level of precision has ever been achieved before. Moreover, stars are known to be variable in brightness, but the only star known to this level of precision during Kepler's formulation phase was the Sun—a single data point! A photometric error budget was developed that assumed stellar variability of 10 ppm (the value for the Sun), leaving 17 ppm for the measurement and ground data processing. This was further subdivided into various contributions from signal shot noise, cosmic rays, read noise and charge transfer efficiency from the focal plane charge coupled devices (CCDs), image smear, pointing jitter, etc.

Many technical and programmatic challenges were encountered during the eventful development phase of the Kepler mission. Programmatic challenges are documented elsewhere [1]. Among the more interesting technical challenges were the ability to verify and validate the photometric performance of Kepler prior to launch, the need to make a last minute change to the focal plane drive electronics design due to an electronic part susceptibility to radiation single event effects, and the various systematic noise sources that were discovered during ground testing of the focal plane readout electronics. These challenges and the steps taken to overcome them are detailed in what follows. Finally, some early and spectacular science results from the mission are summarized.

2. The Design of Kepler

The Kepler space vehicle consists of a Spacecraft bus and Photometer instrument as shown in Figure 1. The Spacecraft provides electrical power from solar panels, provides command and data handling, communicates with the Earth, controls the pointing of the line of sight of the telescope, and performs various housekeeping functions. The Photometer, shown in Figure 2, consists of a Schmidt camera having a spherical primary mirror of 1.4 meter diameter; a Schmidt corrector plate (lens) of 0.95 meter aperture; and a 95 megapixel focal plane array assembly (FPAA) consisting of 42 science CCDs, 4 fine guidance CCDs for pointing control, and the readout electronics on 10 electronics cards. The FPAA is located at the prime focus of the telescope, suspended on four spider legs from the telescope housing. The focal plane array is arranged as 25 modules, with the four corner modules allocated to the fine guidance sensors. Each of the 21 science modules consists of two CCDs. Each of the modules includes a sapphire field flattener lens mounted above the CCDs to correct for field curvature across the module. The fully assembled focal plane array can be seen in Figure 3.

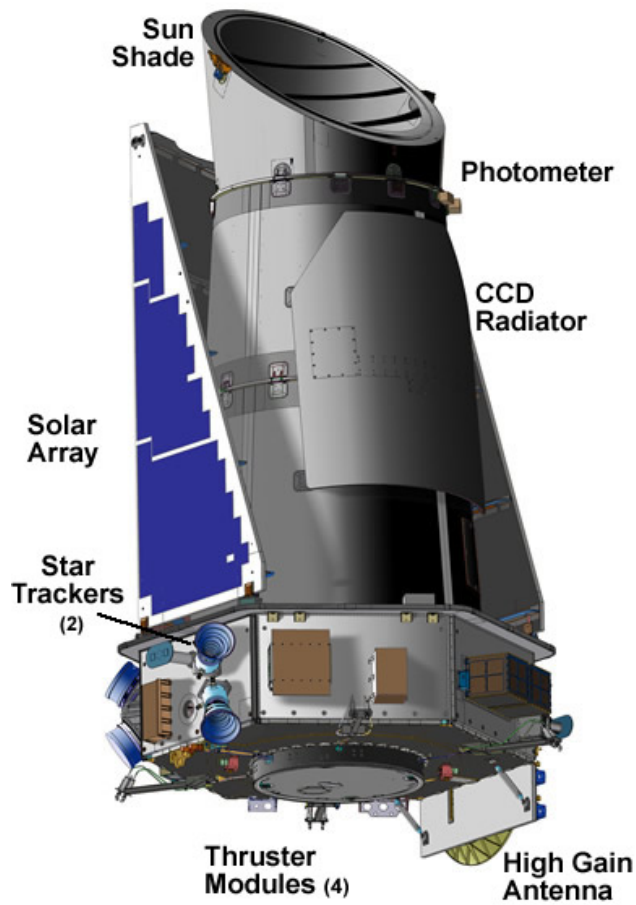

Figure 1. The Kepler space vehicle consists of a spacecraft bus and Photometer instrument.

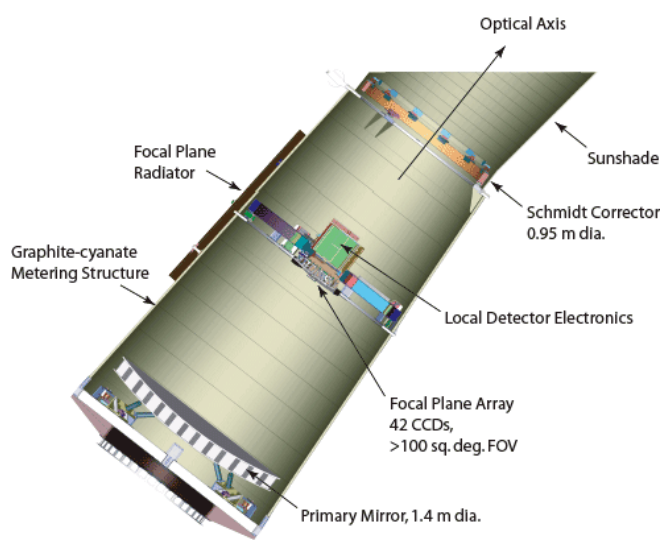

Figure 2. The Kepler Photometer (shown in section view) consists of a primary mirror, Schmidt corrector, and 95 megapixel focal plane array assembly.

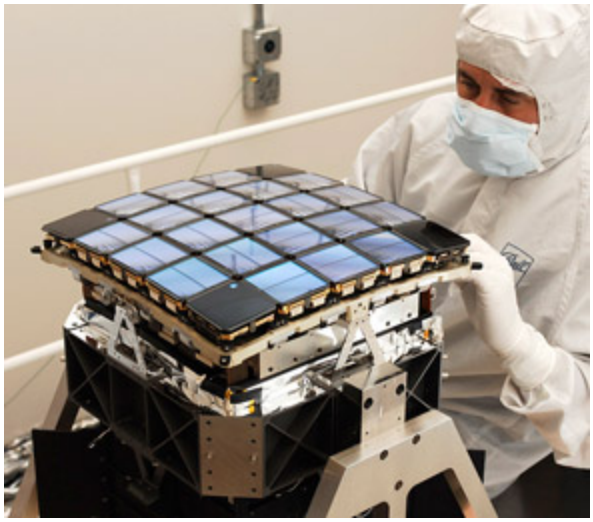

Figure 3. The Kepler Focal Plane Array Assembly (FPAA) includes 42 science CCDs and 4 find guidance CCDs (at the corners) forming a 95 megapixel camera.

Some key performance requirements for the Kepler mission include:

- Measurement of photometric data on at least 100,000 target stars every 30 minutes
- Photometric precision of 20 ppm on a 12th magnitude G2V dwarf star (having 10 ppm stellar variability) over a 6.5 hour integration
- Pointing stability of 0.009 arc seconds (3-sigma) per axis over any period of time 15 minutes or longer in duration
- Mission lifetime of at least 3.5 years

In order to meet the extremely high photometric precision requirement it was decided to place Kepler into an Earth-trailing solar orbit rather than into orbit around the Earth. This has the advantage of a stable thermal environment necessary to achieve very stable temperatures. Stable temperatures are in turn key to stable electronics performance, stable optical metrology, and stable pointing stability and repeatability. Since it is necessary to keep the solar array pointed toward the Sun, the Kepler space vehicle must be rotated around the telescope line of sight 90 degrees every three months. This changes the portion of the focal plane that each target star falls on, and therefore changes the CCD and readout electronics chain associated with the photometric measurement. In constructing the stellar light curves it is therefore necessary to calibrate these and other systematic effects in the data.

3. Verifying and Validating Photometric Precision

This section will discuss the original plan to perform end-to-end testing of the Kepler Photometer by projecting into the telescope a collimated beam of light that could simulate a planet transit. Originally this had been envisioned to simulate an Earth size transit of 0.01%, which was later descoped to a Giant planet transit of 1%. Eventually this was considered impracticable, even though much effort had been put into building the stimulus that would have been mounted above the Photometer in a thermal-vacuum chamber test. Ultimately and end-to-end test on the flight vehicle had to be abandoned in favor of a laboratory test using a single string flight-like CCD detector module and readout electronics chain, where a 0.01% transit could be simulated for reasonable cost. This was combined with noise testing of the flight focal plane array assembly, and analysis of the effect of pointing jitter and other systematic noise sources. The intellectual arc of this V&V approach was crucial to obtaining sufficient confidence that Kepler could achieve its mission objectives. The reality of not being able to perform end-to-end V&V on real flight systems is likely to become increasingly common. Piece-wise validation approaches must be approached with utmost caution and rigor.

4. Single Event Effect Susceptibility

This section will describe a late discovery that the CMOS clock driver component used to drive the serial and parallel clocks of the focal plane CCDs was susceptible to catastrophic single event radiation failures. While this was the same component used to drive the CCDs on the HiRISE camera of the Mars Reconnaissance Orbiter (MRO), the HiRISE design operated the part at a lower voltage. Radiation screening tests performed at the Brookhaven National Laboratory were, upon review, deemed to be insufficient due to inadequate penetrating energy of the beam used in testing. Subsequent tests performed by the Kepler team at Texas A&M revealed that the Kepler mission would likely fail due to in-flight failures for the design that had been built and assembled. All work on the focal plane array assembly stopped while a solution was sought. Ultimately, it was decided to reduce the operating voltage based on limited statistics available from radiation testing. Lowering the voltage caused non-ideal performance of the readout electronics, contributing to systematic noise effects that impacted photometric performance in portions of the focal plane, as well as reduced full well capacity of the CCDs, making bright stars more subject to blooming. This experience cost the project several months of schedule, and was instrumental in triggering a replan of the entire projects.

5. Systematic Noise Sources

The most difficult aspect of achieving photometric performance is the control and calibration of systematic noise sources. Noise at the ppm level was present in several

forms due in part to the decision early on in the mission to descope the flowdown of requirements to the detector readout electronics level, and to limit the engineering unit to a single set of electronics boards. Various cross-talk noise sources and other design deficiencies were therefore not detected until late in the test phase of the Photometer. As there was no time to change the electronics design, methods for identifying the calibrating the systematic noise sources in the ground processing software were needed. This section will review the various approaches taken to deal with the late-breaking noise challenges, and review what might have been done differently to avoid some of the greatest difficulties.

5. EARLY MISSION SCIENCE RESULTS

This section will summarize the planet discoveries and other science results from the first year of mission operations. Many of the discovery announcements are scheduled for public release in January 2011, and will be included in this paper.

REFERENCES

[1] Fanson, J., Livesay, L., Frerking, M., Cooke, B., "Management and Systems Engineering of the Kepler Mission," Proc. SPIE 7738, (2010) [2] Michael Hammer and James Champy, Reengineering the Corporation, New York: Harper Business, 1993.

BIOGRAPHY

James Fanson *is a project manager at the NASA Jet Propulsion Laboratory. He managed the Kepler project from the final year before launch through the start of routine science operations. He is the recipient of two NASA Outstanding Leadership Medals and the NASA Exceptional Engineering Achievement Medal. He received his Ph.D. in Applied Mechanics from Caltech in 2006 and joined JPL at that time.*