Call for White Papers: Soliciting Community Input for Alternate Science Investigations for the Kepler Spacecraft

An open solicitation from the Kepler Project office at NASA Ames Research Center
2 Aug. 2013

Introduction and Purpose

The Kepler spacecraft was launched in 2009 and has been operational for four years. The spacecraft is in a heliocentric orbit currently about 0.5 AU from Earth. The nominal Kepler mission, to determine the frequency of Earth-size exoplanets orbiting solar type stars, was discussed in detail in a special ApJ Letters issue – April 2010, Vol. 713. In July 2012 and again in May 2013, Kepler lost first one then two of its four reaction wheels. These reaction wheels were used to keep the telescope in fine point during long duration (weeks to months) observations of the Kepler field of view. Kepler requires three reaction wheels to deliver the high-precision photometry necessary for small exoplanet detection. If one of the two reaction wheels cannot be returned to operation, it is unlikely that the spacecraft will resume the nominal Kepler exoplanet and astrophysics mission.

The purpose of this call for white papers is to solicit community input for alternate science investigations that may be performed using Kepler and are consistent with its probable two-wheel performance. Herein, we provide initial information as to the preliminary assessment of the pointing ability of the Kepler spacecraft using only two reaction wheels. In addition, we provide baseline information on the Kepler focal plane imaging CCD array (Kepler's only instrument) and give estimates of the photometric performance that may be possible in two-wheel mode. While the pointing and photometric performance estimates are preliminary, they should provide an adequate basis for assessing the scientific opportunities that might be accessible to a two-wheel Kepler mission. If an appropriate science case(s) and cost envelope is found, the repurposed mission will continue to be operated out of NASA Ames Research Center and make use of the nominal mission project office personnel and expertise already in place.

All white papers submitted in response to this call will be made publicly available through the Kepler Mission web page (http://kepler.arc.nasa.gov). No funding is available under this call. The use of any ideas presented in submitted white papers for a repurposed Kepler mission does not imply a commitment on the part of NASA or the Kepler Project to provide future funding for the submitting party.

Proposed science cases should advance the goals and objectives of the NASA astrophysics program as articulated in the 2010 SMD science plan http://science.nasa.gov/medialibrary/2010/08/30/2010SciencePlan_TAGGED.pdf and need not be limited to the exoplanet science or stellar astrophysics that previously characterized the nominal Kepler mission.

Since two-wheel operation will not provide pointing stability on par with the original mission performance, the photometric precision of two wheel observations will likely be degraded with respect to the nominal mission. Therefore, in addition to proposals for science investigations, we are soliciting proposals for new and innovative techniques for instrument operation, data collection, instrument calibration, and data analysis that can improve photometric precision under conditions of degraded pointing stability, possibly including significant linear image motion.

Examples of such proposals might include improved calibration of intra-pixel responsivity variations, data analysis techniques suitable for extraction of photometry from trailed images or modifications of data collection methods, such as significant changes to the current usage of masks to select pixels for coaddition and downlink. Consideration will also be given to modifications of instrument operation, including possible changes to flight software to take better advantage of hardware capabilities. Note that changes to flight software are very time and cost intensive.

Expected Schedule

At this time, the expected plan and schedule leading to a repurposed Kepler mission is as follows:

2 Aug 2013 – Release of call for white papers
3 Sept 2013 – Due date for submission of white papers
1 Nov 2013 – End of review period for white papers, report submitted to NASA HQ
1 Feb 2014 – Senior Review proposal for repurposed Kepler submitted to NASA HQ
Spring 2014 – Decision for funding for repurposed Kepler spacecraft
Summer 2014 – Begin new science program(s)

A Two-Wheel Kepler Mission

Kepler has only one instrument, a large field of view CCD focal plane array. The array has no filters and no shutter. The large focal plane array, consisting of 42 separate CCDs (27 micron pixels, 3.98 arcsec/pixel) covers ~100 sq. degrees on the sky. The large field of view is a curved focal surface that makes use of sapphire field-flattening lenses covering each CCD module. The spectral band-pass of the instrument is broad with >40% response from 420nm to 850nm. Fig. 1 shows the band-pass and the separate response curves of the photometer. Koch et al. 2010, ApJ, Vol. 713, L79 provide details of the focal plane CCD array and the nominal instrument performance. Point-response functions for stars during the nominal mission are discussed in Bryson et al., 2010, ApJ, Vol. 713, L97. Details of the detectors and their properties such as read noise, QE, etc., are presented in Caldwell et al., 2010, ApJ, Vol. 713, L92. This paper also discusses the electronic artifacts noted in the Kepler detector array. The process used to calibrate the Kepler pixels and produce light curves and other products during the nominal mission are discussed in Jenkins et al., 2010, ApJ, Vol. 713, L87.

Kepler's exquisite photometric precision during the nominal mission was due to its ability to finely point at one position on the sky. Additionally, Kepler continued this pointing for weeks to months generating long-term light curves. The two-wheel mission will not be able to point as well or for as long a time period, but the pointing capability may be sufficient to enable alternative science investigations.

During the nominal mission, a V=12 star provided 1.4 x 10^6 electrons in a single 6 sec integration. This means that stars brighter than ~11.5 saturate the pixels in this time period. Kepler mostly used 30-minute samples and obtained a photometric precision for a 12^{th} magnitude star in 6.5 hours that was near 30 ppm. We expect this same count rate for a V=12 star, but because the image is spread out over more pixels, the increased read noise and larger responsivity variations will reduce the delivered photometric precision. We provide an estimate for the expected two-wheel photometric performance below.

The Kepler Instrument Handbook available at http://keplergo.arc.nasa.gov/Documentation.shtml provides a large amount of information on the Kepler focal plane array. The sections listed below are particularly helpful: 2.1, 2.2, 2.5, 2.6, 2.7, 2.8, 3, 4.3, 4.6, 4.7, 4.8, 4.9, 4.10, 4.11, 4.16, 5, 6.2, 6.3, 6.6, 7.3, 7.4, 7.5.

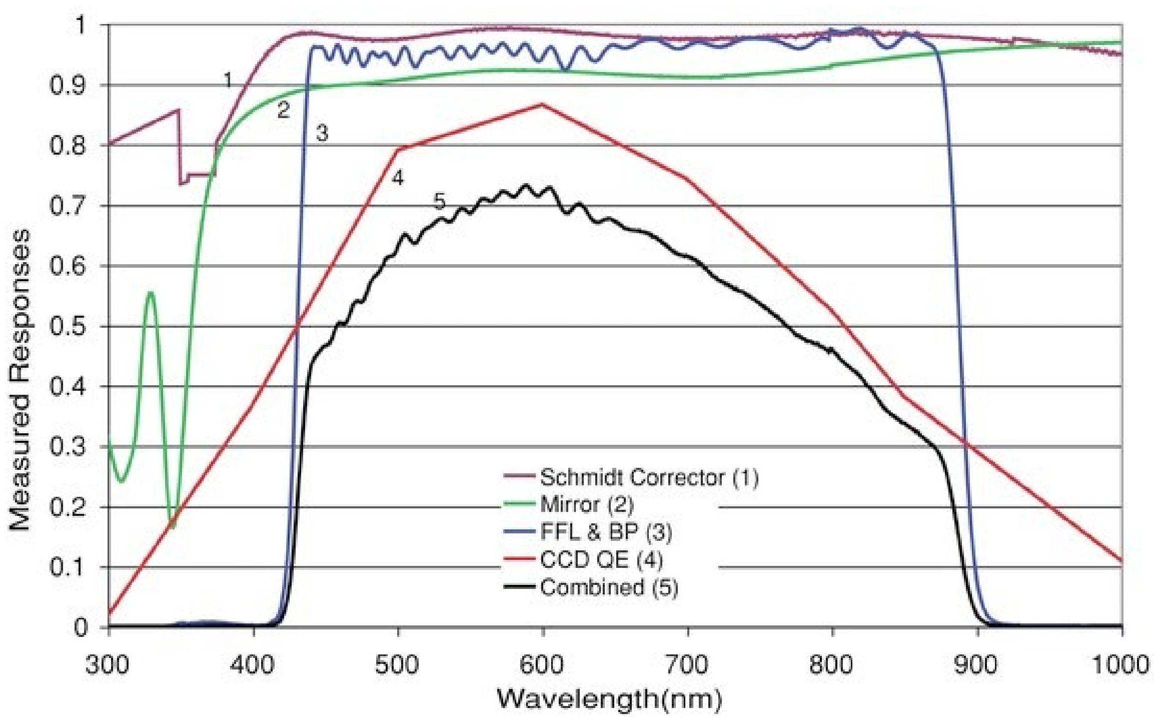

Figure 1 – Spectral band-pass response functions for the Kepler focal plane array.

Kepler Two-wheel Pointing Performance

Ball Aerospace, who developed and built Kepler, has performed a preliminary study of the possible pointing performance of Kepler using 2 reaction wheels and (minimal) thrusters. We summarize that study below and caution the reader that this is a preliminary work and any detailed operation of the Kepler spacecraft using only 2 reaction wheels will depend on the specific science program and the details of how that program is implemented.

The Kepler spacecraft, Figure 2, can be controlled using two reaction wheels with high accuracy. This accuracy does not provide the performance of the original three or four-wheel attitude control system, but it may still be sufficient to provide for alternative science. The anticipated pointing mode is accomplished with existing attitude control system capabilities, without uploading new software, by appropriately changing flight table values.

The proposed mode uses the star trackers and the two remaining reaction wheels to accurately point the two axes of the payload boresight for up to several days with no thruster activity during the pointing session. Appropriate balancing of the solar torque minimizes roll about boresight. This point-drift mode is schematically illustrated in Fig. 3. Note that the preliminary value of a 1.4 degree drift over a 4 day period may cause an object that started on a particular CCD channel (about 1 deg X 1 deg) to drift off that CCD on the Kepler focal plane during the ~4 day time period. The time of the drift (that is, time on target) is a controllable parameter up to the approximate 4-day limit. It is likely there will be preferred, optimal orientations of the spacecraft with respect to the sun that limit available targets in some sky locations.

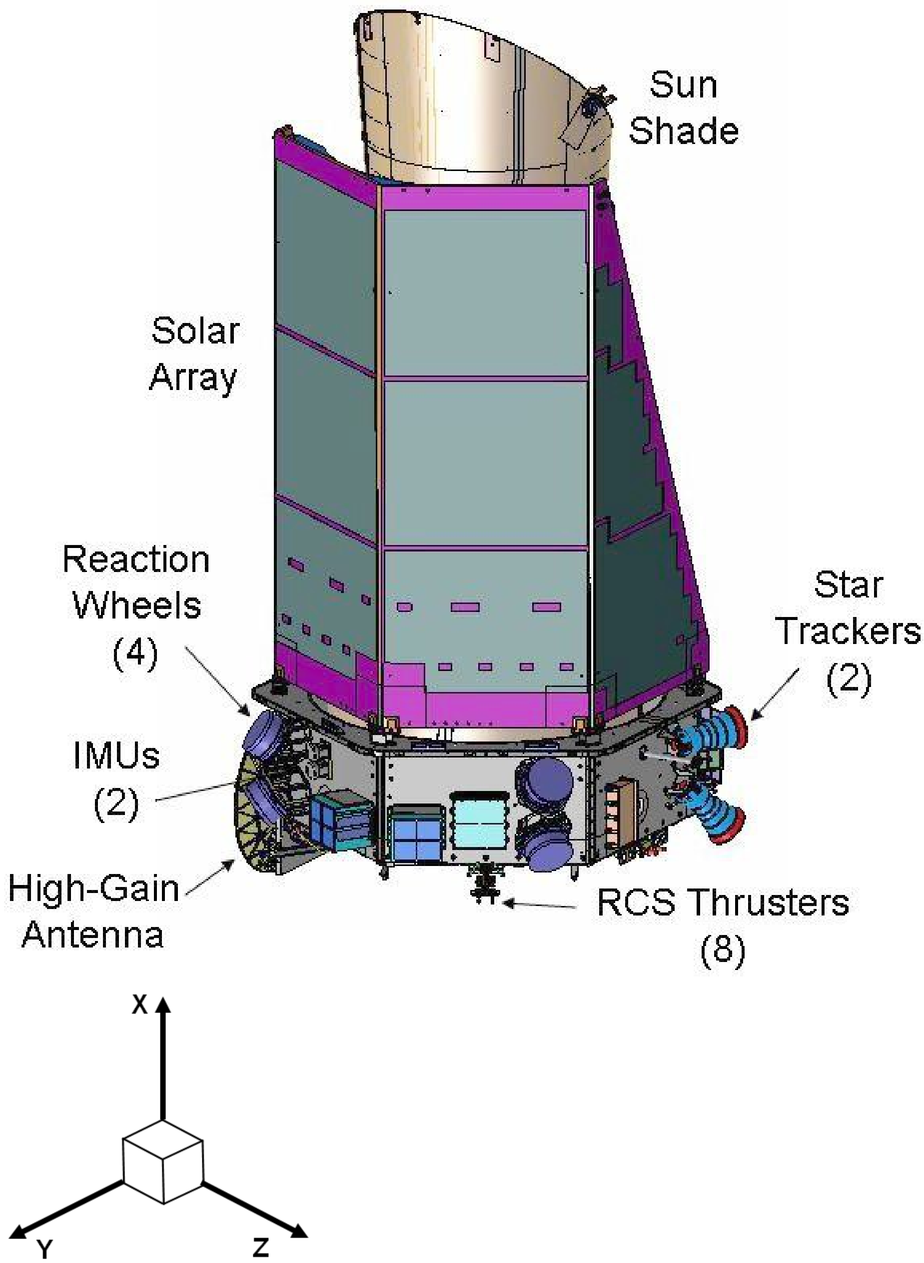

Figure 2 – Kepler Spacecraft Attitude Components. The sun is in the y direction and the boresight (viewing direction) is in the x direction.

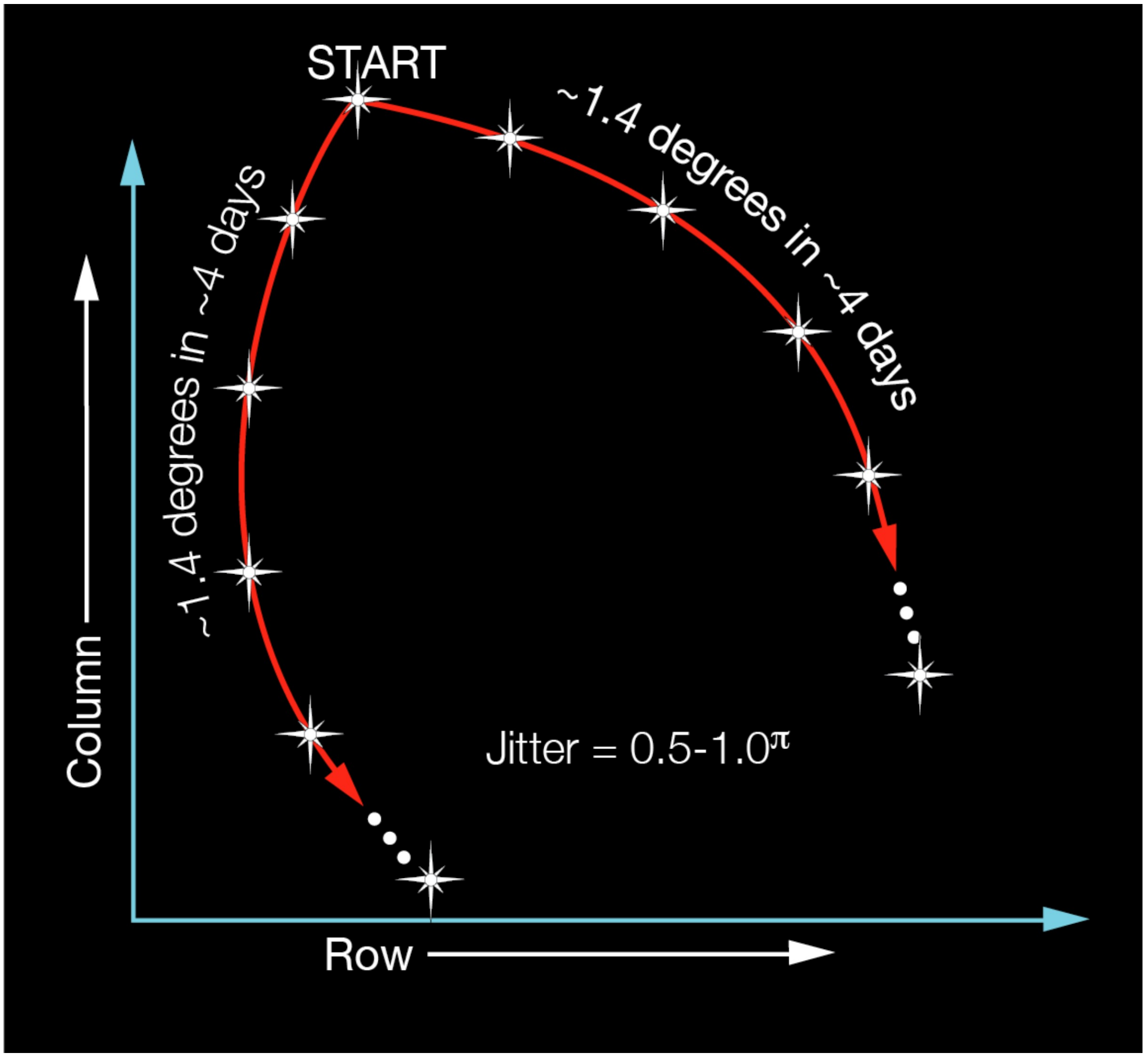

Figure 3 – Schematic view of two possible point-drift mode observations on a CCD. During a ~4 day period, the spacecraft can hold a target to within a jitter of ~0.5-1.0 arcsec along a drift line that is estimated to be ~1.4 degrees in length. A reset of the pointing brings the observation back to near the start point. The rate of drift is estimated to be approximately 0.9 arcsec/minute (~1 pixel in ~5 minutes) or possibly less. The path of a target during this time period will inscribe an arc shape on the focal plane.

Ideal Pointing Scenario

In the ideal scenario, the spacecraft is reoriented to point at a desired target, approximately 90+/-45 deg away from the sun, with an about boresight attitude which has only a pure –Z-axis solar torque. This ensures power and the proper disturbance environment. This can be accomplished for both northern or southern sky attitudes. For example, the ecliptic poles (+/-45 degrees) appear to be very favorable; high galactic latitudes would be good for a part of each year, and the ecliptic plane is good only at longitudes 90 and 270 degrees from the

Sun and at +/-45 degrees. Pointing closer than 45 degrees from the sun and in the anti-sun direction, +/-135 degrees, is also forbidden.

Once a pointing position has been established, Kepler can point to an accuracy of ~1” and maintain 1” jitter about the drift line for less than or equal to ~4 days as shown in Fig. 3. The values of these parameters depend on the selected spacecraft attitude chosen. During pointing, no thruster activity is required. After the time period of days, the spacecraft and reaction wheel momentum must be reset which would involve pointing to a new attitude (new target) and/or back to the original target attitude. The time of such a momentum reset is estimated to be 30 min to 1 hour.

Science data downlink via Ka band communication (high data rate communication) is accomplished by earth pointing the antenna and will require modest thruster use, similar to that used in the nominal mission.

Focal Plane Array Readout and Integration Times

Kepler spacecraft software does not physically window regions of interest in the CCDs. Instead, all pixels are read out for each frame, and manipulated on-board. Target and Aperture definitions, predetermined and uploaded, determine which of the pixels are read out, compressed, transmitted to the on-board data recorder, and downlinked. Individual Kepler targets are read out and stored as postage stamp type pixel groups called target apertures. These apertures are currently defined to match the brightness and resulting PSF of the target. The target apertures do not need to be rectangular, or even contiguous. The apertures can contain up to 32767 pixels each, so several apertures can be used to read out a single entire CCD. In flight, the aperture must be one of 1024 configurable on-board aperture definitions. The maximum number of targets is 170,000 and independently the maximum number of pixels that can be specified is 5.44 million. Using all 5.44 million pixels takes about 12 minutes of time to readout and store on board. Less pixels used, require less time to store. Sections 2.6-2.8 of the Kepler Instrument Handbook provide additional details related to target setup.

Kepler can also obtain, store and return the entire CCD pixel array in a full-frame image (FFI). These pixels may be coadded in a manner similar to the target pixel images but are not compressed by the current flight software. During the nominal mission an FFI was obtained about every month. Examples of such images can be found at the MAST Kepler archive. A FFI can be taken with any of the above allowed integration times, but requires about 20 minutes to store in on-board memory. The on-board recorder can hold 42 such images.

During the nominal Kepler mission, two integration times were used; long cadence or 30 minute samples, and short cadence or 1 minute cadence. Short cadence targets are limited to no more than 512 across the entire focal plane.

The allowed integration times are formed by the sequence “25, 26, 27... 77 times a base of 0.10379 sec. Thus, one can use integration times of 2.5, 2.6, … 8 sec with a 0.51895 sec readout time for each integration. Not all of these possible times have been tested, but any of them can be selected without flight software modification. However, not all combinations of these parameters are allowable, limited in part by the time needed to transfer the coadded image to the data recorder, which is approximately 12 minutes for the full 5.44 million pixels. Altering this mode of specifying the observations will require flight software changes.

Expected Photometric Performance

Exact values for the expected relative photometric performance of a two-wheel Kepler mission are not known. Given the preliminary operation mode described above, we estimate and model the photometry to provide values as best guesses as to the photometric performance. These values will depend on the actual operation of the spacecraft, in particular pointing stability, and there may be ways to improve these values during post-processing using data reduction techniques (e.g., differential photometry; Howell et al., 1988, AJ, 95, 247, image differencing, or PRF fitting; Still et al., 2013) or CCD focal plane models (e.g., Merline and Howell, 1995, Exp. Astronomy, 6, 163; De Ridder et al., 2006, MNRAS, 365, 595).

Using the nominal mission photometric values, our expectations of two-wheel pointing abilities, and both real data during times of poor pointing (nominal mission coarse point) as well as focal plane models, we estimate that a 1 minute integration under +/-0.5 arcsec pointing conditions could provide approximately 300-600 parts per million photometry (0.3 - 0.6 mmag) rms scatter per measurement for a 12th magnitude star. This might increase to about 1 mmag for +/-1 arcsec pointing. However, since the target moves through an arc across the focal plane over time, falling on different pixels, the pixel sensitivity variations may limit the overall relative photometry to ~0.3-1%. These values are preliminary and some work indicates that better precision might be obtainable. Data analysis, modeling, coaddition, and averaging of the data, post-collection, can increase the overall photometric precision, but will depend on the brightness of the source and the techniques applied.

Programmatic information

White papers should be no longer than 10 pages, including tables, figures, and all cited references. Because only preliminary values for the pointing ability and expected photometric precision are available in this call, it is expected that the white papers will be less detailed than typically found in a formal proposal submission. No budget funds are available for work related to these white papers nor should any budget be included or monetary exchange be expected.

Each white paper should provide the names and affiliations of the authors, an abstract, a description of the science project proposed, how the focal plane will be used (target apertures or FFI's), planned integration time(s), expected data storage need, data reduction or analysis plans, what class of science target is involved (point sources, extended objects, etc.), target durations (1 observation, observations over days, weeks, etc.), how long the science program should be run, and what scientific impact will occur during and after the proposed project.

White papers are to be delivered in electronic form as PDF files and should be sent to the Kepler Project Scientist, Dr. Steve B. Howell, at steve.b.howell@nasa.gov.
White papers are due on 3 September 2013. Note, this is not a *ROSES* call nor are *NSPIRES* submissions involved.

Questions related to this call should be directed to the Kepler Project Scientist either via email or by phone at 650-604-4238. Questions will be directed as needed to the appropriate person and answered, as well as posted to the Kepler Science Center web site: http://keplergo.arc.nasa.gov/.

References

1. Kepler Instrument Handbook

2. Data Characteristics Handbook
Chapters 1-5 are fairly specific to the nominal mission operation, but do contain some generally good information. Chapter 6 is particularly useful.

The above two documents can be obtained at
http://keplergo.arc.nasa.gov/Documentation.shtml

3. Special Issue of Astrophysical Letters, 2010, vol. 713 (available via ADS)
Of particular interest are:
Koch et al., page 79
Jenkins et al., page 87
Caldwell et al., page 92
Bryson et al., page 97

4. Data Release Notes
http://keplergo.arc.nasa.gov/Documentation.shtml