The *Kepler Mission*: A Search for Terrestrial Planets

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The *Kepler mission* was launched March 6, 2009 and is NASA's first mission capable of finding earth-size planets orbiting in the habitable zones of other stars. Kepler will determine the distribution of earth-size planets in the habitable zones of solar-like stars[1]. After a two month commissioning activity Kepler began science observations and will continue to monitor > 100,000 dwarf stars simultaneously over the primary mission life of 3.5 years, with a capability to extend these observations for a total of 7 years. Precision differential photometry will be used to detect the periodic signals of transiting planets via small changes in the light of their host stars. *Kepler* will also support asteroseismology science by measuring the pressure-mode (p-mode) oscillations of selected stars.

Transits of a solar-size star by an earth-size planet will produce a reduction in the stare light of 84 parts per million (ppm) or 0.008%. For a statistically significant detection, the minimum single transit Signal to Noise Ratio (SNR) requirement is taken to be 4σ, leading to a combined average significance of 8σ for 4 such transits. The Kepler combined differential photometric precision must therefore be less than 21 ppm binned at 6.5 hours (half of a central transit duration). The detection threshold for terrestrial habitable zone planets in the Kepler data pipeline is set at 7σ, yielding a

[1] Earth-size planets are terrestrial or rocky planets with masses ranging from 0.5 to 10 earth-masses. Smaller planets can't maintain a life-sustaining atmosphere and larger planets retain primordial atmospheres. The habitable zone (HZ) for given star is defined as the region through which planets orbiting there have the potential for liquid surface water, a key building-block of life.

detection rate of 84% while controlling the total number of expected false alarms to no more than one for the entire experiment.

Given this design, the mission will be capable of not only detecting Earth analogs, but a wide range of planetary types and characteristics ranging from Mars-size objects and orbital periods of days to gas-giants and decade long orbits. The mission is designed to survey the full range of spectral-types of dwarf stars. Three or more transits of a star with a statistically consistent period, brightness change and duration provide a rigorous method of detection. From the relative brightness change the planet size can be calculated. From the period the orbital size can be calculated using Kepler's 3rd law of planetary motion and its location relative to the HZ determined.

Key considerations when looking for planetary transits are the probability for the orbital plane to be aligned along the line of sight and the number of stars to monitor. The probability of orbital alignment is simply the ratio of the stellar diameter to the orbital diameter. For the Sun-Earth analogy the probability is 0.5%. Hence, one needs to monitor many thousands of stars before one can arrive at a statistically meaningful result, null or otherwise. Also, a sequence of transits with a consistent period, depth and duration must be detected to be confident and to confirm the existence of a planet.

The Kepler Observatory or "Flight Segment" consist of a large field of view (FOV) photometer and a spacecraft bus. The Kepler Flight Segment was launched on a Delta II rocket into an Earth-trailing heliocentric orbit, such that after 3.5 years the spacecraft will have drifted less than 0.5 AU away from the earth. The Photometer is a Schmidt camera design consisting of a graphite-cyanate ester metering structure, sunshade, 95 cm diameter Schmidt corrector, a 1.4 m diameter primary mirror, field-flattening lenses and an array of 42 CCDs with an active FOV of greater than 100 square degrees. The CCDs are back-illuminated devices with dual outputs and 1024x2200 27 µm pixels. The CCDs are passively cooled by a radiator panel. For 103,000 planetary target stars the CCD data are accumulated and co-added for 30 minutes before storage on the spacecraft's solid state recorder. Approximately 512 targets assigned to a succession of different target stars are co-added at a 1 minute cadence for support p-mode asteroseismology and other non-transit science. Since the targets will be pre-selected, the entire image is not stored for downlink but rather only the pixels relevant to each star. This amounts to only about 3% of the pixels being stored, saving a tremendous amount of on-board storage and communications link time. Additionally, a data compression scheme is employed to further reduce storage and transmission requirements. The Photometer does not have a shutter and the only moving parts are three focus and tilt adjustment mechanisms under the primary mirror and the one-time deployable dust cover.

The spacecraft provides the necessary support functions for the photometer including power, pointing control, and data systems. The spacecraft offers three-axis stabilization. Fine guidance sensors are mounted on the scientific focal plane. The entire mission is spent viewing a single star field centered near the constellation of Cygnus. The only attitude maneuvers occur every three months when the spacecraft is rotated about the photometer axis by 90° to maintain the solar array pointed towards the Sun and the radiator towards deep space. Given Kepler's heliocentric orbit, there are no disturbances induced by geo-magnetic moments, gravity gradient or atmospheric drag; only a steady torque due to solar pressure. Precision pointing stability is afforded by reaction wheel assemblies for which periodic momentum de-saturation maneuvers are provided by the hydrazine reaction control system that was used to de-spin and de-tumble the spacecraft following separation from the launch vehicle. No propulsive capability for orbital delta-V correction is required since the spacecraft drift-away rate was constrained by the launch vehicle's injection dispersion errors.

Uplink commanding and downlink real-time engineering data transmission are performed using omni-directional X-band antennas. All stored science and engineering data are downlinked using a high-gain Ka-band system. The solar arrays are rigidly mounted to the spacecraft and also help to provide shielding of the Photometer from the Sun. The only moving parts on the spacecraft bus are the reaction wheels. All spacecraft sub-systems are fully redundant. During Science Operations, regular "housekeeping" communications with the spacecraft are planned to occur approximately twice weekly and playback of the stored science data is downlinked once per month. The antennas of NASA's Deep Space Network are used to support the Kepler uplink and downlink communication needs.

The Kepler Ground Segment includes a collection of facilities, software, processes, and procedures used to operate the Flight Segment and analyze the data. Overall mission direction is provided from the Mission Management and Science Offices hosted by the Science Operations Center (SOC) at NASA Ames Research Center in Mountain View, California. Strategic mission planning and target selection is done at the SOC. Target selection leverages a Kepler-unique input catalog produced by a pre-launch Stellar Classification Program – based on ground-based observations which support separation of the smaller solar-type dwarf stars from giant stars[2]. Flight Segment operations management, tactical mission planning, sequence validation, and engineering trend analysis is provided by a Flight Planning Center (FPC) at Ball Aerospace Technologies Corporation in Boulder, Colorado. Command and data processing, Flight Segment health & status monitoring, and DSN scheduling is the responsibility of the Mission Operations Center (MOC) at the Laboratory for Astronomy and Solar Physics (LASP) in Boulder, Colorado. Uplink and downlink telecommunications use NASA's DSN 34 meter antennas located in Goldstone, California; Madrid, Spain; and Canberra, Australia. Navigation and orbit propagation is provided by the Jet Propulsion Laboratory.

The Data Management Center (DMC) at the Space Telescope Science Institute in Baltimore, Maryland receives the "raw" telemetry data and performs pixel-level calibration. The resulting calibrated data set is archived by the DMC and forwarded to the SOC for further processing. The SOC processing includes generation of calibrated photometric light curves and transit detection. STScI also provides p-mode analysis. After an extensive data validation process, follow-up observations on each planetary candidate will be performed. The Follow-up Observing Program (FOP) is necessary to eliminate intrinsic false positives due to grazing-eclipsing binaries and extrinsic false positives due to background eclipsing binaries or discriminate between terrestrial transits of the target star and giant planet transits of a background star. In some cases the FOP should also be able to measure the mass of the largest planets using ground observations, which together with estimates of planet diameters derived from Kepler transit depth measurements can be combined to determine the density of the planets.

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[2] Main sequence dwarf stars are of primary interest as they are longer-lived than giant stars and hence more likely to

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host habitable planets and because transit signals from earth-size planets are easier to detect around smaller stars given (larger obscuration ratio).