CASE STUDY BY NATIONAL SPACE DAY'24
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Case Study Problem Statement –

Challenges and Innovations in Exoplanet Detection and Characterization with TESS (Transiting Exoplanet Survey Satellite)

Introduction - The Transiting Exoplanet Survey Satellite (TESS) is a NASA Explorer-class mission focused on discovering planets transiting bright dwarf stars. By performing differential time-series photometry, TESS detects temporary drops in star brightness caused by planetary transits, enabling follow-up measurements of planet masses and atmospheres. Over a two-year near all-sky survey, TESS is expected to find over a thousand planets smaller than Neptune, including numerous Earth-sized ones. Operating from an elliptical orbit with a 13.7-day period, TESS uses four wide-field CCD cameras with a 600–1050 nm band-pass to capture images every 2 seconds. The cameras feature long-pass and anti-reflection coatings to enhance sensitivity, especially for redder wavelengths, facilitating observations of small red stars with small planets. The CCDs are read out at a rate of 625 pixels per second.

Background – The Transiting Exoplanet Survey Satellite has significantly advanced the search for exoplanets by focusing on bright, nearby stars across nearly the entire sky. By employing the transit method – where a planet passes in front of its host star, causing a temporary dip in the star's brightness – TESS has discovered thousands of exoplanet candidates. Unlike NASA's kepler mission, which revolutionized exoplanetary science but focused on stars too faint for detailed follow-up, TESS specifically targets the nearest and brightest stars. This approach enables the detection of smaller planets, particularly those smaller than Neptune, and allows for detailed follow-up studies, including spectroscopy to measure planetary masses and atmospheric compositions. Despite these advancements, identifying and characterizing Earth-sized planets in habitable zone remains a significant challenge.

Questions 1 –

Data Processing and Analysis

How does TESS handle data processing to minimize noise and artifacts caused by cosmic rays, spacecraft jitter or other environmental factors? Explain the algorithms or techniques used to ensure high-precision photometry

Solution –

TESS employs several sophisticated data processing techniques to minimize noise and artifacts caused by cosmic rays, spacecraft jitter, and other environmental factors, ensuring high-precision photometry. Here's an overview of how TESS handles data processing and analysis:

1. Data Collection and Preprocessing

- Raw Image Acquisition: TESS captures raw images every 2 seconds using its CCD cameras. These images contain both stellar light and various sources of noise, including cosmic rays and electronic noise.
- Calibration: The raw images undergo calibration to correct for known instrumental effects, such as bias, dark current, and flat-field variations. This step helps to standardize the data before further processing.

2. Cosmic Ray Removal

- Outlier Detection: Cosmic rays often manifest as sharp, transient spikes in the data. TESS employs outlier detection algorithms to identify and flag these events.
- Median Filtering: To mitigate the impact of cosmic rays, a median filter or other smoothing techniques are applied. These filters compare the pixel values across consecutive frames and replace extreme outliers

with more typical values, thereby reducing the influence of cosmic rays on the photometry.

3. Spacecraft Jitter Correction

- Jitter Modelling: Spacecraft jitter, or small, unintended movements of the spacecraft, can cause the star’s image to move slightly on the CCD, introducing noise. TESS uses attitude control data to model and correct for these movements.
- Image Centroiding: The spacecraft's jitter is mitigated by tracking the centroid of each star's image. By accurately determining the star's position in each frame, TESS can adjust the photometric measurements to account for any shifts caused by jitter.
- Motion Correction Algorithms: Algorithms are applied to remove the photometric noise induced by these small motions, helping to stabilize the light curves.

4. Light Curve Extraction

- Aperture Photometry: TESS typically uses aperture photometry to extract light curves from the calibrated images. A circular or elliptical aperture is placed around each star, summing the pixel values within this region to measure the star's brightness over time.
- Optimal Aperture Selection: The size and shape of the aperture are carefully selected to maximize the signal-to-noise ratio (SNR) while minimizing contamination from nearby stars or background noise.
- Background Subtraction: To further enhance precision, background light (from sources such as skyglow, scattered light, and zodiacal light) is estimated and subtracted from the star's signal.

5. Noise Reduction and Detrending

- PCA and Gaussian Processes: Principal Component Analysis (PCA) and Gaussian Process Regression are used to model and remove systematic trends in the data that might be caused by instrumental or environmental effects.
- Systematic Error Correction (Cotrending Basis Vectors): TESS uses cotrending basis vectors, derived from trends observed across many stars, to correct systematic errors common to all light curves. This method helps isolate the intrinsic variability of individual stars from systematic trends.

- Fourier Filtering: High-frequency noise is often reduced using Fourier filtering techniques, which help in isolating the periodic signals of transiting planets from random noise.

6. **Planet Detection**

- Transit Search Algorithms: TESS uses algorithms like the Box-Least Squares (BLS) method to search for periodic dips in the light curves, indicative of transiting planets. The BLS algorithm is particularly effective at detecting the box-shaped signals characteristic of planetary transits.
- Signal Validation: Detected signals are further validated through statistical tests to differentiate between genuine planetary transits and false positives caused by noise or other astrophysical phenomena (e.g., binary stars).

7. **Data Validation and Quality Assurance**

- Quality Flags: Each light curve and detected event is assigned quality flags that indicate potential issues, such as data gaps or periods of high noise. This allows astronomers to assess the reliability of the data.
- Human Review and Machine Learning: While automated algorithms do most of the heavy lifting, human experts and machine learning models also review the data to ensure high-quality detections and minimize false positives.

Question -2 –

Orbit Maintenance and Stability

Given TESS's highly elliptical orbit, describe the methods used to maintain orbital stability and how orbital perturbations are managed. What role does the moon's gravity play in stabilizing TESS's orbit, and how often are orbit corrections required?

Solution –

1-Elliptical Orbit and Orbital Stability –

TESS's orbit is carefully designed to minimize the effects of perturbations and to avoid regions of strong gravitational influence from the Earth and Moon. The spacecraft's perigee (closest point to Earth) is around 108,000 km, and its apogee (farthest point) is about 375,000 km. This allows TESS to spend most of its time far from Earth, reducing the influence of Earth's gravity.

The 2:1 resonance with the Moon is key to maintaining long-term orbital stability. This resonance ensures that TESS and the Moon regularly "reset" their relative positions, helping to cancel out cumulative gravitational effects that could destabilize the orbit over time.

2. Role of the Moon's Gravity –

The Moon's gravity plays a crucial role in stabilizing TESS's orbit. By being in a 2:1 resonance with the Moon, TESS benefits from periodic gravitational assists from the Moon that help maintain its orbit. These assists are subtle but effective in countering small perturbations that might otherwise accumulate and cause the orbit to drift.

3. Long-Term Stability –

The careful balance between gravitational forces, the 2:1 resonance, and the occasional use of thrusters ensures that TESS can maintain its highly elliptical orbit over the long term. This stability is critical for achieving the mission's scientific goals of continuous exoplanet observation.

TESS's orbital stability is maintained through a combination of the Moon's gravitational influence, the resonance of its orbit with the Moon, and occasional thruster adjustments. This approach minimizes the need for frequent orbit corrections while ensuring that TESS remains in a stable, efficient orbit for exoplanet discovery.

Question 3 –

Creative

What do you think are the potential limitations of TESS's ability to detect Earth-like exoplanets in the habitable zone, and how might future missions overcome these challenges?

Solution –

In the search for life in the cosmos, NASA's Transiting Exoplanet Survey Satellite (TESS) mission has already monitored about 74% of the sky for transiting extrasolar planets, including potentially habitable worlds. However, TESS only observed a fraction of the stars long enough to be able to find planets like Earth.

1. **Observational Duration**:
   - TESS observed about 74% of the sky during its two-year primary mission.
   - It monitored several hundred thousand stars but only observed a fraction of them long enough to find planets similar to Earth.
   - Future missions with longer observation windows could improve this limitation.
2. **Signal Detection and Confirmation**:
   - TESS detects planets when they transit in front of their host stars, causing a dip in starlight.
   - However, other factors (instrumental noise, binary stars, etc.) can create similar signals.
   - Confirming these detections often requires follow-up observations from other telescopes or instruments.
3. **Earth-Like Planet Rarity**:
   - Earth-sized planets in the habitable zone are relatively rare.
   - TESS has identified some candidates, but finding more requires extensive surveying.
   - Future missions could expand the search to more stars and regions of the sky.
4. **Stellar Variability and Noise**:
   - Stellar activity (flares, spots, etc.) can introduce noise in photometric data.
   - TESS aims to correct for this, but it remains a challenge.
   - Improved algorithms and data processing techniques can mitigate stellar variability effects.
5. **Spitzer Space Observatory Confirmation**:

- For critical discoveries like the Earth-sized exoplanet TOI-700d, TESS relied on confirmation from the Spitzer Space Observatory.
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Question 5 –

Suppose any new planet P discovered which has a luminosity of 3.186 × 10^26 and distance between the discovered planet and nearest star is 9.013562101 × 10^10 m then find the average temperature of the planet. And if water freezes at 273 K and boils at 373 K, then what will be the range of habitable zones that occur? Let absorbity be 0.5.

Solution –

For calculating the average temperature of planet we use Stefan-Boltzmann law:

$$T_P = \left[\frac{(1 - A) \cdot l}{16 \cdot \sigma \cdot \pi \cdot d^2}\right]^{\frac{1}{4}}$$

Where:

- A is the albedo (reflectivity) of the planet.
- L is the luminosity of the nearest star.
- σ is the Stefan-Boltzmann constant $(5.67 \times 10^{-8} w_m {-}^2 K^4)$
- d is the distance between the star and the planet.

Given:

- L=3.186×10^{26} W
- d=9.013562101×10^{10} m
- A = 0.5A=0.5 (Absorbity is 1−A1 - A1−A)

calculate the temperature:

$$\text{Tp} = \left(\frac{(1 - 0.5) \cdot 3 \cdot 186\ \text{X}10^{26}}{\left(16.\pi \cdot 5 \cdot 67 \times 10^{-8}\right)\ (9.013562101\ \text{X}\ 10^{10}\ ))^2}\right)^{\frac{1}{4}}$$

$$\text{Tp} = 316.24\ \text{K}$$

the average temperature of the planet P is approximately 316.24 K.

Range of Habitable zone :

To find the range of the habitable zone where liquid water could exist (i.e., the temperature range between 273 K and 373 K), we need to reverse-engineer the temperature equation to solve for distance d

$$T_P = \left[\frac{(1-A)\cdot \mathrm{L}}{16\cdot\sigma\cdot\pi\cdot \mathrm{T}^4}\right]^{\frac{1}{2}}$$

For the lower bound (freezing point of water at 273 K):

$$d\ min = \left(\frac{(1-0.5)\cdot 3\cdot 186\ \mathrm{X}10^{26}}{(16.\pi\cdot 5\cdot 67\times 10^{-8})\ (273)^4}\right)^{\frac{1}{2}}$$

For the upper bound (boiling point of water at 373 K):

$$d\ \mathrm{max} = \left(\frac{(1-0.5)\cdot 3\cdot 186\ \mathrm{X}10^{26}}{(16.\pi\cdot 5\cdot 67\times 10^{-8})\ (373)^4}\right)^{\frac{1}{2}}$$

Let’s calculate these:

For $d\ min$ (273 K):

$$d\ min = \left(\frac{1\cdot 593\ \mathrm{X}10^{26}}{(2.888\times 5.57\ \times 10^{-8})\ \ (5.598\ \times 10^{9})}\right)^{\frac{1}{2}}$$

Simplifying

dmin ≈ 2.823×1011 m

For $d\ max$ (373 K):

D max ≈ 2.823×1010 m

The habitable zone range would be from **~2.823 × 10^10 m** to **~2.823 × 10^11 m**.

Question 5 –

Long-Term Mission Sustainability

What are the challenges associated with the long-term sustainability of the TESS mission, including the potential for mechanical failures, degradation of instruments, or depletion of fuel? How are these challenges mitigated to ensure mission longevity?

Solution-

Mechanical Failures

Challenge: Mechanical components of the spacecraft, such as moving parts in the reaction wheels or gyroscopes, are prone to wear and tear over time, which could lead to failures that impact the satellite's ability to maintain its orientation and perform its observations.

Redundancy: TESS is designed with redundant systems, such as multiple reaction wheels, to ensure that if one fails, the others can compensate.

Regular Monitoring: The health of mechanical systems is continuously monitored, allowing for early detection of anomalies. This enables ground control to take corrective actions before a failure becomes critical.

Design for Longevity: The mission employs components with long operational lifespans and uses lubricants and materials that are resistant to the harsh conditions of space.

2. Degradation of Instruments

Challenge: Over time, exposure to the space environment, including radiation, micrometeoroids, and thermal cycling, can degrade the performance of TESS's cameras and other scientific instruments. This can lead to a decrease in sensitivity and accuracy in detecting exoplanets.

Radiation-Hardened Components: TESS uses radiation-hardened electronics and materials to protect against damage from cosmic rays and solar radiation.

Shielding: The spacecraft is equipped with shielding to protect its instruments from micrometeoroid impacts and radiation.

Calibration: Regular calibration of the cameras is performed to adjust for any degradation in performance, ensuring that the data remains accurate and reliable.

Extended Mission Planning: The mission team planned for potential instrument degradation by designing the survey to include overlapping observations, which allows for cross-verification of data even if some instruments lose sensitivity.

3. Fuel Depletion

Challenge: TESS requires fuel to perform orbital corrections, maintain its position, and manage its attitude control. Over time, the fuel supply will deplete, which could limit the spacecraft's ability to continue its mission.

Efficient Orbital Design: TESS is in a highly elliptical orbit in a 2:1 resonance with the Moon. This orbit minimizes the need for frequent corrections, thereby conserving fuel. The gravitational influence of the Moon helps stabilize the orbit, reducing the amount of fuel needed for station-keeping.

Fuel Management: The mission carefully monitors and manages fuel usage, planning maneuvers efficiently to extend the mission's life as much as possible.

End-of-Life Planning: As the mission progresses, the team plans for an orderly end-of-life scenario where remaining fuel is used for a final scientific push or to place the spacecraft in a safe orbit, reducing the risk of collision or space debris.

4. Environmental Factors

Challenge: The space environment, including exposure to solar storms, thermal variations, and cosmic radiation, poses a risk to the long-term functionality of TESS.

Mitigation:

Robust Design: The spacecraft is designed to withstand extreme temperatures and radiation levels, with materials and electronics chosen for their durability.

Thermal Management: TESS has a thermal control system to maintain optimal operating temperatures for its instruments and electronics, protecting them from the extreme heat and cold of space.

Monitoring Space Weather: Mission control monitors space weather conditions, such as solar flares, and can place the spacecraft into a protective mode if necessary to shield it from harm.

5. Data Management and Software Updates

Challenge: As the mission progresses, the volume of data collected increases, which can strain data storage and processing capabilities. Additionally, software bugs or outdated algorithms could affect mission performance.

Data Compression and Prioritization: The mission uses data compression techniques to maximize the amount of data that can be sent back to Earth. Critical data is prioritized for transmission.

Software Updates: The mission can receive software updates from Earth, allowing the team to address bugs, improve algorithms, and optimize data collection as new scientific priorities emerge.

Ground-Based Support: A robust ground support team continuously analyzes data and provides feedback to optimize the mission's scientific output.