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Title: Surface Mapping of Earth-like Exoplanets using Single Point Light Curves

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Author Questionnaire

1. Microscopy: Does your protocol involve video microscopy, such as filming a complex dissection or microinjection technique? **N**

2. Software: Does the part of your protocol being filmed demonstrate software usage? **Y**

3. Filming location: Will the filming need to take place in multiple locations (greater than walking distance)? **N**

Introduction

1. Introductory Interview Statements

REQUIRED:

1.1. **Yuk L. Yung**: This protocol can be used to spatially resolve exoplanet features from single-point observations and is essential for evaluating the potential habitability of exoplanets **[1]**.

1.1.1. INTERVIEW: Named talent says the statement above in an interview-style shot, looking slightly off-camera

REQUIRED:

1.2. **Siteng Fan**: This technique can be used to reconstruct two-dimensional surface maps of Earth-like exoplanets and is the first technique being tested with real observations using the Earth as a proxy **[1]**.

1.2.1. INTERVIEW: Named talent says the statement above in an interview-style shot, looking slightly off-camera

OPTIONAL:

1.3. **Siteng Fan**: The mathematics of this technique is straightforward and can be easily adjusted for other observations. One does not need to strictly follow the coding scripts **[1]**.

1.3.1. INTERVIEW: Named talent says the statement above in an interview-style shot, looking slightly off-camera

OPTIONAL:

1.4. **Yuk L. Yung**: Visual demonstration of this technique is important, because one picture is worth a thousand words **[1]**.

1.4.1. INTERVIEW: Named talent says the statement above in an interview-style shot, looking slightly off-camera

Protocol

2. Programming Setup and Multi-Wavelength Light Curve Visualization

2.1. After setting up the programming environment for the attached code **[1-TXT]**, enter the command to install Anaconda with Python 3.7 onto the system **[2-TXT]**.

2.1.1. WIDE: Talent navigating to website **TEXT: Linux os required; Healpy package not available on Windows**

2.1.2. SCREEN: screenshot_1: 00:00-00:15 *Video Editor: can speed up* **TEXT: https://docs.anaconda.com/anaconda/install/linux/; Follow instructions as indicated**

2.2. After setting up the programming environment, obtain multi-wavelength light curves, view the geometry from the observations, and run the **PlotTimeSeries.py** command to visualize the data and check their qualities **[1]**.

2.2.1. SCREEN: screenshot_2: 00:00-00:19 *Video Editor: please speed up*

2.3. Then enter the command to generate a geometry figure **[1-TXT]**.

2.3.1. SCREEN: screenshot_2: 00:31-00:43 **TEXT: Adjust parameters as necessary to apply to different observations**

3. Light Curve Surface Information Extraction

3.1. To extract the light curve surface information, run the **Normalize.py** command **[1]**. The output is saved in **NormalizedLightCurve.csv [2]**.

3.1.1. WIDE: Talent running command, with monitor visible in frame

3.1.2. SCREEN: screenshot_2: 00:53-01:10

3.2. Enter the command to visualize the normalized light curves. A normalized light curve figure will be created **[1]**.

3.2.1. SCREEN: screenshot_2: 01:37-01:58 *Video Editor: please speed up*

3.3. Enter the command to decompose the normalized light curves. The resulting time series, singular values, and principal components will be saved in the appropriate output files in .csv **format [1]**.

3.3.1. SCREEN: screenshot_2: 02:10-02:22

3.4. Use the commands to visualize the singular value decomposition result. Figures for the singular values and principal components will be generated **[1]**.

3.4.1. SCREEN: screenshot_2: 03:30-03:40

3.5. Analyze the contributions and corresponding time series of the principal components to determine the one that contains surface information and compare the singular values at the diagonal of singular value matrix. An Earth-like, partially cloudy exoplanet is expected to have two comparable dominant singular values **[1]**.

3.5.1. SCREEN: screenshot_2: 04:05-04:19

3.6. To confirm the selection of the principal component, enter the command to obtain the power spectra of the time series of each principal component. The power spectra will be saved in **Periodogram.csv [1]**.

3.6.1. SCREEN: screenshot_2: 04:41-05:29 *Video Editor: please speed up*

3.7. Enter the command to visualize the periodograms and confirm the selection of the principal component. A periodgram figure will be generated **[1]**.

3.7.1. SCREEN: screenshot_2: 05:51-06:30

3.8. The current plotting code adds dashed lines that represent the annual, semi-annual, diurnal, and half-daily cycles for reference. Select the principal component that contains the surface information and its corresponding time series **[1-TXT]**.

3.8.1. SCREEN: screenshot_2: 06:08-06:15 **TEXT: Change codes for other observations as appropriate**

4. Planetary Surface Map Construction

4.1. To construct a planetary surface map, use the HEALPix (heal picks) Random command to visualize the pixelization method **[1-TXT]**. A HEALPix Random figure will be created **[2]**.

4.1.1. WIDE: Talent entering command **TEXT: HEALPix: Hierarchical Equal Area iso-Latitude Pixelization**

4.1.2. SCREEN: screenshot_3: 00:00-00:11

4.2. The parameter N-sub-side at line 17 at can be changed for different resolutions **[1]**.

4.2.1. SCREEN: screenshot_3: 00:18-00:26

4.3. To determine the weight of each pixel, enter the command. The output will be saved as **W.npz** due to its size **[1]**.

4.3.1. SCREEN: screenshot_3: 00:32-01:03 *Video Editor: please speed up*

4.4. Change the N-sub-side value at line 23 as appropriate for the other resolutions of the retrieved map **[1]**.

4.4.1. SCREEN: screenshot_3: 01:09-01:16

4.5. Use the **PlotWeight.py** command to visualize the weights **[1]**. A number of figures will be created in the **Weight** folder. Merging the figures will allow illustration of how the weight of each pixel changes with time **[2]**.

4.5.1. SCREEN: screenshot_4: 00:02-00:33 *Video Editor: please speed up*

4.5.2. SCREEN: screenshot_4: 00:39-03:54

4.6. Use the **LinearRegression.py** command to solve the linear regression problem **[1]**. The result of pixel values will be saved in the **PixelValue.csv** file **[2]**. The value of lambda at line 16 can be changed for different strengths of regularization as appropriate **[3]**.

4.6.1. SCREEN: screenshot_6: 00:00-00:06

4.6.2. SCREEN: screenshot_6: 01:19-01:29

4.6.3. SCREEN: screenshot_6: 01:52-02:02

4.7. Then run the **PlotMap.py** command to construct the retrieved maps using different regularization parameters **[1]**. Three maps will be generated **[1]**.

4.7.1. SCREEN: screenshot_6: 02:10-02:24 *Video Editor: can speed up*

4.7.2. SCREEN: screenshot_6: 02:43-02:52

4.8. The relationship between the pixel indices and their locations on each map are described in the HEALPix document **[1]**.

4.8.1. SCREEN: screenshot_7: 00:03-00:07

5. Retrieved Map Uncertainty Estimation

5.1. To compute the covariance matrix of each pixel, run the **Covariance.py** command **[1]**. The result will be saved in **Covariance.npz** due to its size **[2]**.

5.1.1. WIDE: Talent entering command, with monitor visible in frame

5.1.2. SCREEN: screenshot_7: 00:26-01:18 *Video Editor: please speed up*

5.2. To visualize the covariance matrix and to map the uncertainty to the retrieved map, run the **PlotCovariance.py** command **[1]**. One Covariance **[2]** and one Uncertainty figure **[3]** will be created **[added?]**.

5.2.1. SCREEN: screenshot_7: 01:31-01:58 *Video Editor: please speed up*

5.2.2. SCREEN: screenshot_7: 01:59-02:00

5.2.3. SCREEN: screenshot_7: 02:09

Added shot: Talent entering command, with monitor visible in frame. Author NOTE: This is combined with 5.1.1, as this step has better visual presentation. Additional NOTE: Not sure if this fits well with the VO

Results

6. Results: Representative Surface Mapping and Analysis

6.1. Here sample multi-wavelength observations of the earth at 9:27 Coordinated Universal Time, February 08, 2017, are shown **[1]**.

6.1.1. LAB MEDIA: Figure 1 *Video Editor: please sequentially add/emphasize images from top left to bottom right*

6.2. Here the time series of the two dominant principal components of the multi-wavelength light curves can be observed **[1]**.

6.2.1. LAB MEDIA: Figure 2

6.3. The time series for the second principal component demonstrates a more regular morphology with an approximately constant daily variation **[1]** and stronger diurnal cycle in its power spectrum than the first principal component **[2]**.

6.3.1. LAB MEDIA: Figure 2 *Video Editor: please emphasize Figure 2C*
6.3.2. LAB MEDIA: Figure 2 *Video Editor: please emphasize Figure 2D*

6.4. A surface map of this proxy exoplanet consisting of the value of the second principal component at each pixel can then be constructed **[1]**.

6.4.1. LAB MEDIA: Figure 3 top map

6.5. Compared to the ground truth of Earth **[1]**, the reconstructed map recovers all major continents after separating the surface information from the clouds **[2]**. The results for the southern hemisphere are worse than those observed for the northern hemisphere due to the cloud cover over the southern oceans **[3]**.

6.5.1. LAB MEDIA: Figure 3 top and middle maps *Video Editor: please emphasize middle map*
6.5.2. LAB MEDIA: Figure 3 top and middle maps *Video Editor: please emphasize red and green signal on top map*
6.5.3. LAB MEDIA: Figure 3 top and middle maps *Video Editor: please emphasize influence of clouds over southern oceans*

6.6. The uncertainty of each pixel value is on the order of 10% of that in the retrieved map, suggesting a good quality of the surface mapping and a positive result **[1]**.

6.6.1. LAB MEDIA: Figure 3 *Video Editor: please emphasize bottom map*

Conclusion

7. Conclusion Interview Statements

7.1. **Siteng Fan**: The critical requirement for applying this protocol to future analyses is confirming that the surface information can be extracted from light curves **[1]**.

7.1.1. INTERVIEW: Named talent says the statement above in an interview-style shot, looking slightly off-camera (3.5.-3.11.)

7.2. **Siteng Fan**: This technique serves as a benchmark in the surface mapping of exoplanets and may be improved with other decomposition and regularization methods for new observations **[1]**.

7.2.1. INTERVIEW: Named talent says the statement above in an interview-style shot, looking slightly off-camera