## The New Worlds Observer:

**Opening Direct Study of Exo-planets Using External Occulters**

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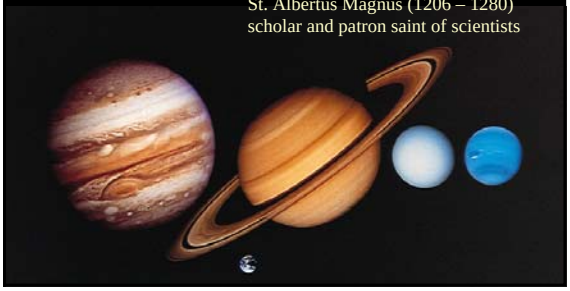
University of Colorado
&
The NASA Institute for Advanced Concepts

1

*Do there exist many worlds, or is there but a single world? This is one of the most noble and exalted questions in the study of Nature.*

St. Albertus Magnus (1206 – 1280)
scholar and patron saint of scientists




## Bringing Science Fiction To Life

3

## Exoplanets

**The Planets That Circle Other Stars**

**There are probably 10,000 within 10pc (30 light years) of the Earth. Indirect means have now found over 200.**

**If we can observe them directly, we will have a new field of astronomy every bit as rich as extragalactic.**

Artists's View of Red Dwarf with Substellar Companion
NASA, ESA, and G. Bacon (STScI) • STScI-PRC06-31b

4

## Boy Have We Got A Problem!

An Earth-like Planet Is 10 Billion Times Fainter Than Its Parent Star

6pack vs Bill Gates entire fortune

AND

Less Than 0.1 Arcseconds Away

One Hubble Resolution Element

Courtesy of N-G

5

## Exploration & Science

**One doesn't discover new lands without consenting to lose sight of the shore for a very long time.**
Andre Gide *(1869 - 1951)*

**Science requires a hypothesis suggesting knowledge of the answer while exploration has no such conceit.**

New Worlds is Exploration First
Science Second

6

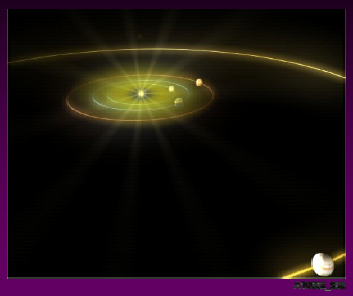
## Indirect Means

Over 200 Exoplanets Now Known

Mostly from Radial Velocity Measurements


7

## Direct Imaging is What We Want



Can We Ever Map Extra-Solar Systems In This Manner?

8

## Terrestrial Planet Finder

- Must be done from space because of the atmosphere
- Telescopes must be corrected to ***PERFECTION***
  - to suppress scatter: λ/5000 surface, 99.999% reflection uniformity
- TPF is *very* difficult
- NASA has not been good to TPF lately.
  - They are on indefinite hold.

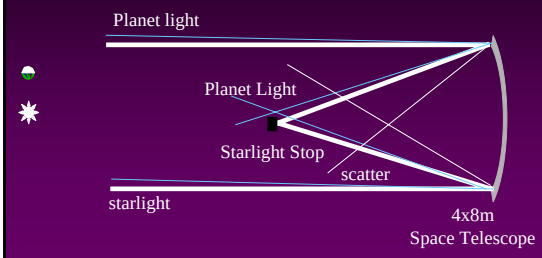
9

## TPF-C
## Terrestrial Planet Finder - Coronagraph

Works in Visible Band

10

## TPF-C
## Visible Light Coronagraph




11

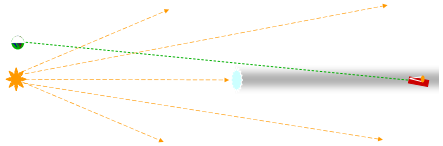
## External Occulters

Let's Resurrect an Old Idea

Spitzer (1962) appears to be the first

Just Keep the Starlight Out of the Telescope

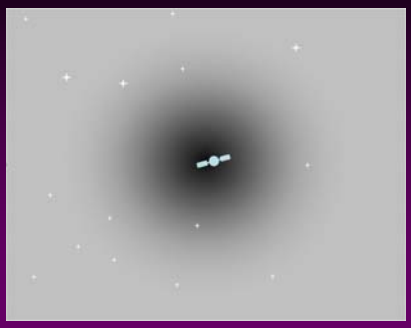
## Occulter Diagram



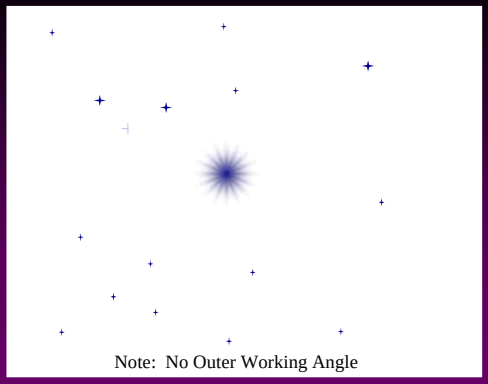
Telescope big enough to collect enough light from planet
Occulter big enough to block star
- Want low transmission on axis and high transmission off axis

Telescope far enough back to have a properly small IWA
No outer working angle: View entire system at once


## Fly the Telescope into the Shadow



15



Note: No Outer Working Angle

16

## The Obstacle

## DIFFRACTION

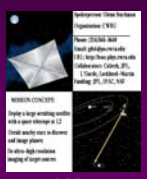
Despite What They Tell You in Sixth Grade
Light Does Not Move In Straight Lines

17

## Occulters

- Several previous programs have looked at occulters
- Used simple geometric shapes
  - Achieved only $10^{-2}$ suppression across a broad spectral band
- With transmissive shades
  - Achieved only $10^{-4}$ suppression despite scatter problem

http://umbras.org/

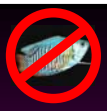


BOSS

Starkman (TRW ca 2000)

18

## Extinguishing Poisson's Spot



- Occulters Have Very Poor Diffraction Performance
  - The 1818 Prediction of Fresnel led to the famous episode of:
  - Poisson's Spot (variously Arago's Spot)
  - Occulters Often Concentrate Light!
- Must satisfy Fresnel Equation, Not Just the Fraunhoffer Equation
- Must Create a Zone That Is:
  - Deep — Below $10^{-10}$ diffraction
  - Wide — A couple meters minimum
  - Broad — Suppress across at least one octave of spectrum
- Must Be Practical
  - Binary — Non-transmitting to avoid scatter
  - Size — Below 150m Diameter
  - Tolerance — Insensitive to microscopic errors

19

## A Solution Exists

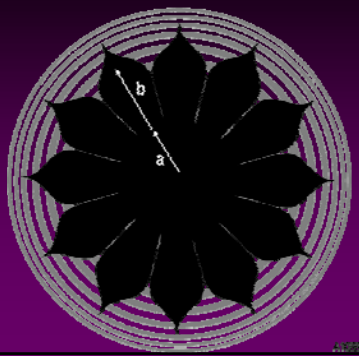
$$A(\rho)=0 \quad \text{for} \quad \rho < a$$

and

$$A(\rho)=1-e^{-\left(\frac{\rho-a}{b}\right)^n} \quad \text{for} \quad \rho > a$$

20

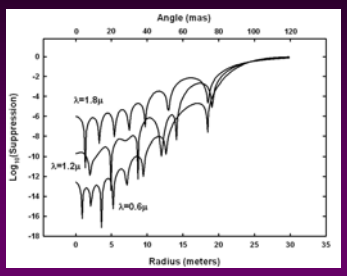
## Binary Shape




21

## Performance

A 50m diameter occulter at 50,000km will reveal Earths at 10pc

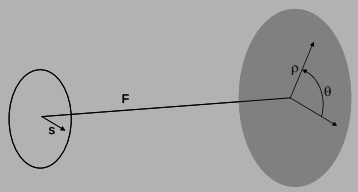



a=b=12.5m
n=6
F=50,000km

22

## Huygens-Fresnel Principle

$$E=\frac{E_0}{i\lambda r}\iint Ae^{ikr}dS$$




23

## Fresnel Approximation

$$E=\frac{E_0 e^{ikF}e^{\frac{iks^2}{2F}}}{i\lambda F}\int_0^{\infty}e^{\frac{ik\rho^2}{2F}}\rho\int_0^{2\pi}A(\theta,\rho)e^{\frac{ik\rho s\cos\theta}{F}}d\theta d\rho$$

Then, if circularly symmetric:

$$E=\frac{E_0 k e^{ikF}e^{\frac{iks^2}{2F}}}{iF}\int_0^{\infty}e^{\frac{ik\rho^2}{2F}}A(\rho)J_0\left(\frac{k\rho s}{F}\right)\rho d\rho$$

24

## Now, Evaluate Candidate Apodization Function

$$A(\rho)=1 \qquad A(\rho)=e^{-\left(\frac{\rho-a}{b}\right)^n}$$

$$E=\frac{k}{iF}\int_0^a e^{\frac{ik\rho^2}{2F}}\rho d\rho+\frac{k}{iF}\int_a^\infty e^{-\frac{(\rho-a)^n}{b^n}+\frac{ik\rho^2}{2F}}\rho d\rho$$

25

## Dimensionless Natural Units

$$\alpha=a\sqrt{\frac{k}{F}}$$

$$\beta=b\sqrt{\frac{k}{F}}$$

$$\tau=\rho\sqrt{\frac{k}{F}}$$

26

## Electric Field at Center:

$$E=\frac{1}{i}\int_0^\alpha e^{\frac{i\tau^2}{2}}\tau d\tau+\frac{1}{i}\int_\alpha^\infty e^{\frac{i\tau^2}{2}-\left(\frac{\tau-\alpha}{\beta}\right)^n}\tau d\tau$$

$$E=1-e^{\frac{i\alpha^2}{2}}+\frac{1}{i}\int_\alpha^\infty e^{\frac{i\tau^2}{2}-\left(\frac{\tau-\alpha}{\beta}\right)^n}\tau d\tau$$

27

## Integrate by Parts

Yields E = 1+R where R is small as desired
And

$$R=n\int_\alpha^\infty e^{\frac{i\tau^2}{2}}e^{-\left(\frac{\tau-\alpha}{\beta}\right)^n}\left(\frac{\tau-\alpha}{\beta}\right)^{n-1}d\tau$$

This closed-form integral represents the electric field at the center of the shadow

28

## Continue Integrating by Parts

Drop Small Terms

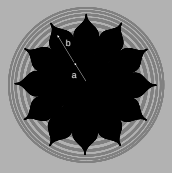
Dominant Term

$$R\le\frac{n!}{\beta^n}\frac{1}{\alpha}\left(\frac{1}{\alpha}\right)^{n-1}=\frac{n!}{\alpha^n\beta^n}$$

**If $\beta^2 >> n$**

29

## Binary Apodization




Difference between petals and circularly symmetric apodization.

$$R=\frac{k}{2\pi F}\int_a^\infty e^{\frac{ik\rho^2}{2F}}\rho\int_0^{2\pi}\left[A(\rho,\theta)e^{\frac{-ik\rho s\cos\theta}{F}}-A(\rho)e^{\frac{-ik\rho s\cos\theta}{F}}\right]d\theta d\rho$$

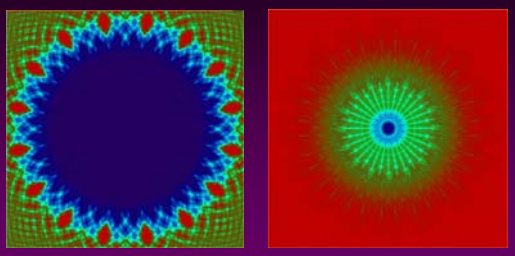
30

## New Code

- Still Need Computer Simulations
  - e.g. Some Disagreement about Minimum Number of Petals
  - Direct Fresnel 2-d integral is very slow
- Princeton, Goddard , NGST, CU All Working on this
- new cu code
  - Integrate Fresnel by parts
  - Yields edge integral --- like Green's Theorem
  - Very Fast
  - Will Allow Diffraction Analysis with Any Error

31

## Shadow of 16 Petal Mask

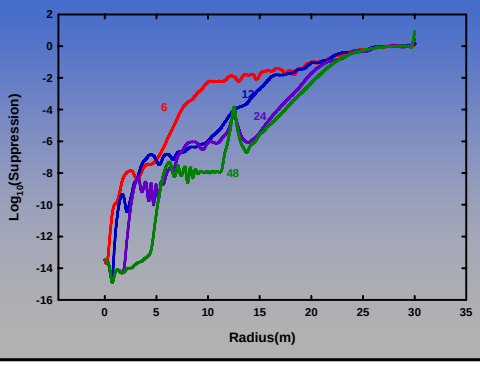


Linear Log

32

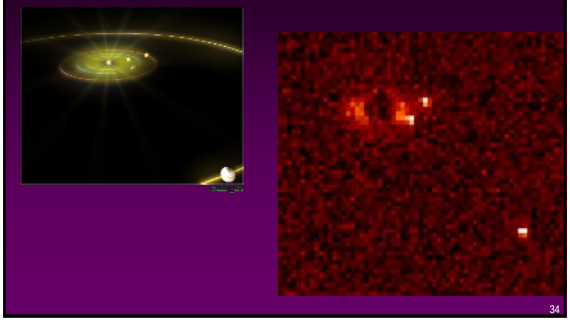
Petal Profiles

## Effect of Petal Number




33

## Simulated Solar System



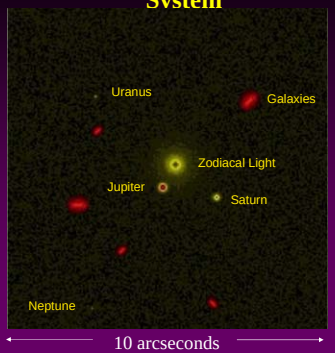
34

## New World Observer Architecture

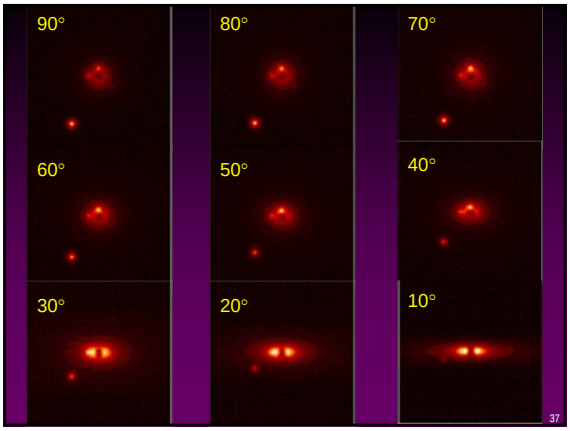
- 4m Telescope Diameter Breakpoint
- Two Starshades – one small and fast
- Very Powerful Scientifically
- Cost comparable to other missions on table

35

## The First Image of Solar System



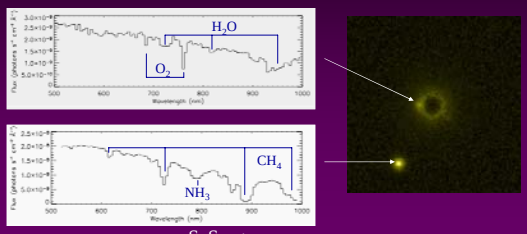

36



37

## Spectroscopy

☞R > 100 spectroscopy will distinguish terrestrial atmospheres from Jovian with modeling




S. Seager

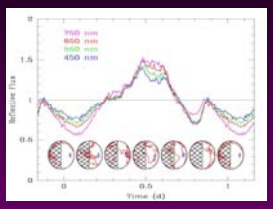
38

## *Spectroscopic Biomarkers*

| | |
|---|---|
| Water | Necessary for habitability |
| Oxygen | Free oxygen results only from active plant life |
| Ozone | Results from free oxygen |
| Nitrous Oxide | Another gas produced by living organisms |
| Methane | Life indicator if oxygen also present |
| Vegetation | Red edge of vegetation at 750nm |

39

## Photometry




*Calculated Photometry of Cloudless Earth as it Rotates*

It Should Be Possible to Detect Oceans and Continents!

40

## NWO Science

☞ Result of Nature interviews
- ➢Many discussions with press and other interested parties

☞ It is Life Seeking that EVERYBODY wants
- ➢ Just finding water planets enough, but its not what motivates the public

☞ Can there be a bigger or more important question for astronomers?

☞ New Worlds Observer can do it
- ➢ $2-3 Billion and 10 years


41

## Implementation

No pessimist ever discovered the secret of the stars or sailed an uncharted land, or opened a new doorway for the human spirit.

Helen Keller *(1880 - 1968)*

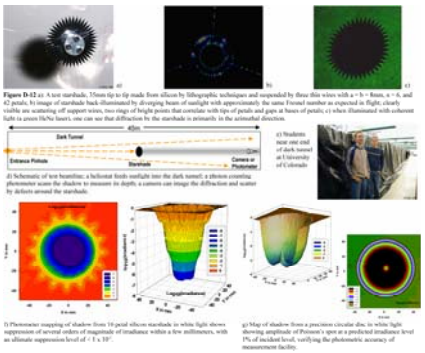
42

## Tall Poles

- Deployment of 35m shade to mm class tolerance
- Acquiring and holding line of sight
- Fuel usage, orbits and number of targets
- Stray Light – particularly solar

43

## Lab Studies



## Tolerance Analysis

- Proceeds by perturbation analysis
- Pitch or Yaw error – foreshortened to 1-ε in one dimension

$$E = \frac{k}{2\pi i F} e^{ikF} \left[ \begin{array}{l} (1-\varepsilon)\int e^{\frac{ikz^2}{2F}} \int e^{\frac{ik\alpha^2(1-\varepsilon)^2}{2F}} dydz + \\ (1-\varepsilon)\int e^{\frac{ikz^2}{2F}} \int e^{\frac{ik\alpha^2(1-\varepsilon)^2}{2F}} e^{-\left(\frac{\sqrt{\beta^2+\alpha^2(1-\varepsilon)^2}-a}{b}\right)^n} dydz \end{array} \right]$$

Where z=x/(1-ε)

Reduces to

$$R = n\varepsilon \int_0^\infty e^{\frac{i(\beta y+\alpha)^2}{2}} e^{-y^n} y^{n-1} dy$$

Proving $R = \varepsilon R_{cs}$

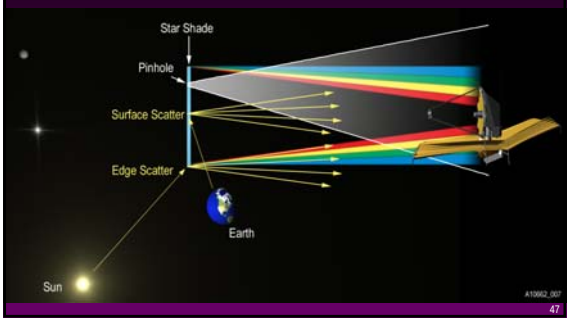
45

## Starshade Tolerances

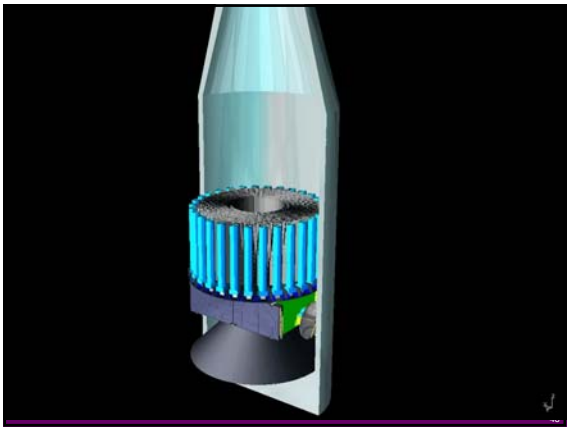
- Position
  - Lateral — Several Meters
  - Distance — Many Kilometers
- Angle
  - Rotational — None
  - Pitch/Yaw — Many Degrees
- Shape
  - Truncation — 1mm
  - Scale — 10%
  - Blob — 3cm² or greater
- Holes
  - Single Hole — 3cm²
  - Pinholes — 3cm² total

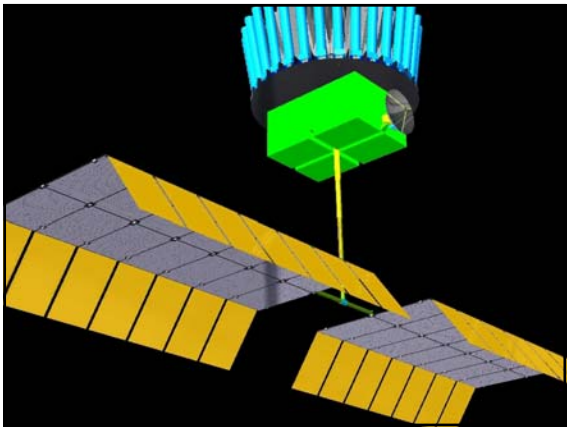
46

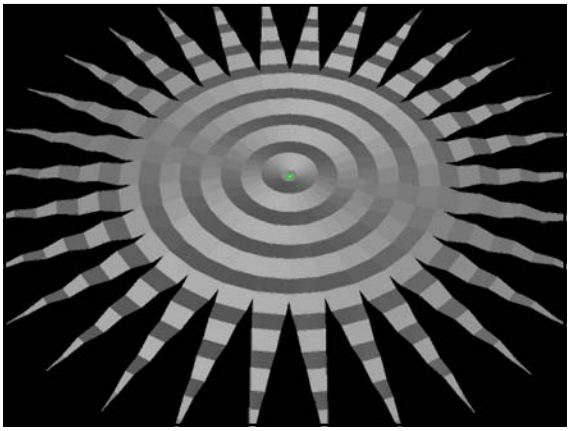
## Scatter Control
### View Nightside



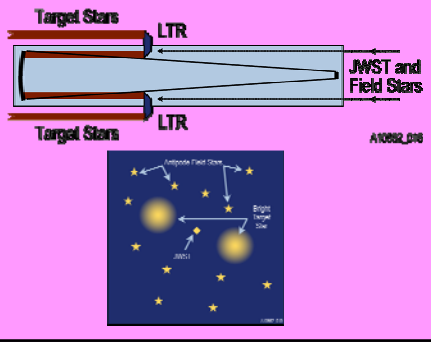

47



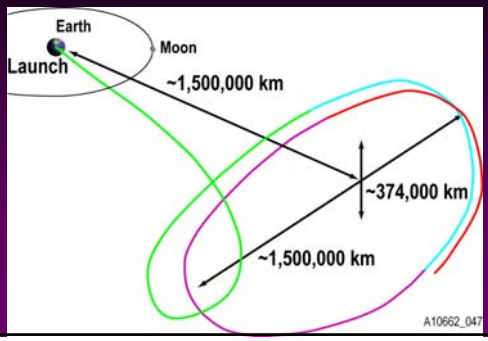




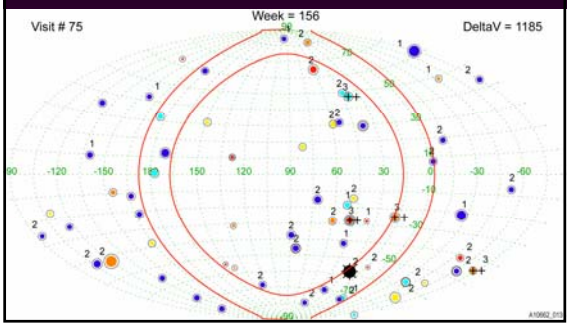
## Alignment acquisition & hold




## L2 Orbit Favorable




## Planning the Mission



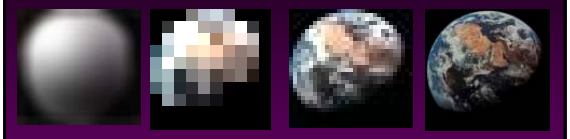

## The New Worlds Imager

Earth at 200km resolution. Oceans, continents and clouds are visible.

Young Water Planet

JPL

## TRUE PLANET IMAGING

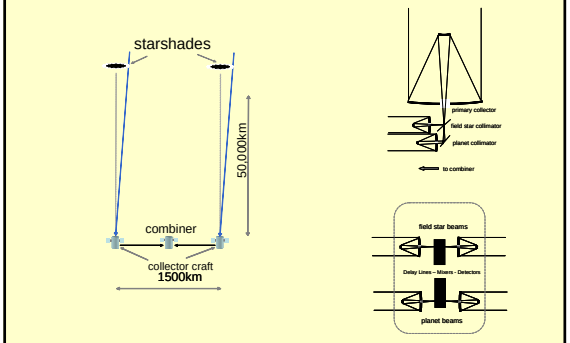


3000 km 1000 km 300 km 100 km

**Earth Viewed at Improving Resolution**

55

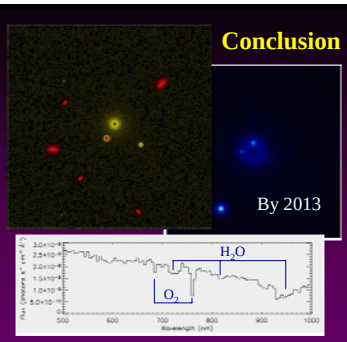
## NWI Concept




## Solar System Survey at 300km Resolution

57

## Conclusion





There is nothing in the above mission that the people in this room could not implement today.

Money for such a mission will be available in two years. This is an obvious candidate.

58