Science Requirements and Spectral Regions

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Science Requirements I
General Mission Assumptions

Sky Coverage Req.= 60%, Goal= 90%

This is a sunshield concept issue that also reflects on free-flyer vs. truss systems

Mission Duration Req. = 5, Goal = 10 (years)

This is mostly about expendibles -cryogens and thruster fuels. It is helped by lower mass spacecraft. For fall-away orbits there is a communications issue.

Nominal Planet Earth size, 270K @ 7-17µm

Earth albedo sets an average closer to 250K.

Planet detection/characterization 50% of time

Allows 860 days of planet system observations.

Non-nuclear power

Does not seem to have major design effects

Status of the problem

Phil [Crane] and I discussed the probability of finding Earths with TPF. How far out will TPF have to look: 3 pc? 10 pc? 15 pc (TPF baseline)? Or 50 pc? The fundamental answer is that we simply do not know how frequent small, rocky planets are. Opinions range from omni-present (my prejudice) to very rare.

C.A. Beichman

memo to Anne Kinney

TPF Science and Technology

TPF is an attempt simultaneously to make a major advance in science and technology - to look for Earth-like planets elsewhere. We know almost nothing about either other Earth-like planets, or the systems in which they reside. We think the dust clouds around ~1/3 of all forming stars are pre-planetary systems, and we have as yet no way of eliminating the possibility that all of them form planetary systems, and yet we are requested that our first look for planetary systems should require us to search around 150 stars! And it is out to where stars and planets are 25 times fainter than the nearest stars, and 5 times closer spaced That is a giant leap for mankind. But is that big of a first step really necessary?

You will see that every clever trick found to solve this problem requires costly technology advances. We are threatened with delay because of cost, and we would have delay anyway because our technology is not yet ready. So as we look at the science requirements and the concepts, we keep being reminded that what we need is not more cleverness, but less cost, less technological progress, but still to make that astronomical advance!

Science Requirements II
Planet Detection I

 # Stars (F-K) surveyed (R=3,SNR=5) Req. = 150, Goal = 500

Was set by original misinterpretation of giant planet spectroscopic search.

 # stars implies ~15pc, needs new discussion. Star types needs a new discussion.

 # Scans for CO2/ H2O (R=3,SNR=10) Req. = 30, Goal = 100

Requires approx. 80% observing time as survey.

 # Scans for Ozone/strong CH4 (R=20,SNR=25) Req.=5, Goal=25

Would need approx 5.6 times observing time as item 1 for same distances

Spectral Band Req = 7-17μm Goal 3-23μm

Short wavelengths pose extreme problems and would be major drivers of cost - if possible at all. Difficulty steadily increases to shorter λ. Rms allowed error = 40nm@20μm and 1nm@7μm

Spectral Resolution Req. = 20, Goal = 100

~20 can be done with prisms and dichroics. 100 needs a grating.

Science Requirements III
Planet Detection II

Max distance of ozone detection Req=10pc Goal = 20pc

The survey to 15pc takes most of the time. Reducing the distance to 10pc makes the ozone detection 1.6 times as long as the first survey.

Minimum distance of planet detection Req =3pc Goal =2pc

Nearest good candidate is Epsilon Eridani at 3.2pc. Lalande 21185 @2pc.

Exozodiacal Dust Req = Solar system level Goal = 10x SS.

Dustier systems need higher angular resolution, which is hard at any wavelength. Easier to look for less dusty systems further away.

Follow up surveys are uniformly distributed through the volume

We interpret this to apply only to the CO2/H2O survey.

Point Source sensitivity 5σ,2hrs@12μm. R=3

The tasks are equivalent to spending 1.8 days per object in the initial survey. Short exposures are not needed for the science. This requirement forces

better nulling on brighter stars, and will play into increased demands on feed-forward precision of the servo loop controlling the null phase.

Science Requirements IV
High Resolution Imaging

We understand that all high resolution imaging requirements have been removed. Astrophysical imaging is still desired. We have examined the requirements, and no system met all the requirements, however some systems met resolution requirements at shorter wavelengths.

The mode of study will be to design devices optimized for the planet studies, and then to explore :

1) *What astrophysical imaging is possible without extra cost, and loss of planet study performance.*

2) *How much astrophysical imaging can be accomplished by modest increases in cost, and modest losses in planet studies performance.*

Book vs. Study Missions

Architecture Study

	Year 1	Year 2	Year 3	Year 4	Year 5	TOTAL
Cool+Checkout	0.5	0	0	0	0	0.5
Planet search	0.4	0.25	0	0	0	0.65
H2O + CO2	0	0.3	0.2	0	0	0.5
Ozone	0	0	0.4	0.4	0.3	1.10
Astro. imaging	0.1	0.45	0.4	0.7	0.7	2.25

TPF Book

	Year 1	Year 2	Year 3	Year 4	Year 5	TOTAL
Cool+Checkout	0.2	0	0	0	0	0.2
Planet search	0.5	0.5	0.2	0.1	0.1	1.4
H2O + CO2	0.1	0.2	0.4	0.4	0.3	1.4
Ozone	0.1	0.1	0.1	0.2	0.2	0.7
Astro. Imaging	0.1	0.2	0.3	0.3	0.4	1.3

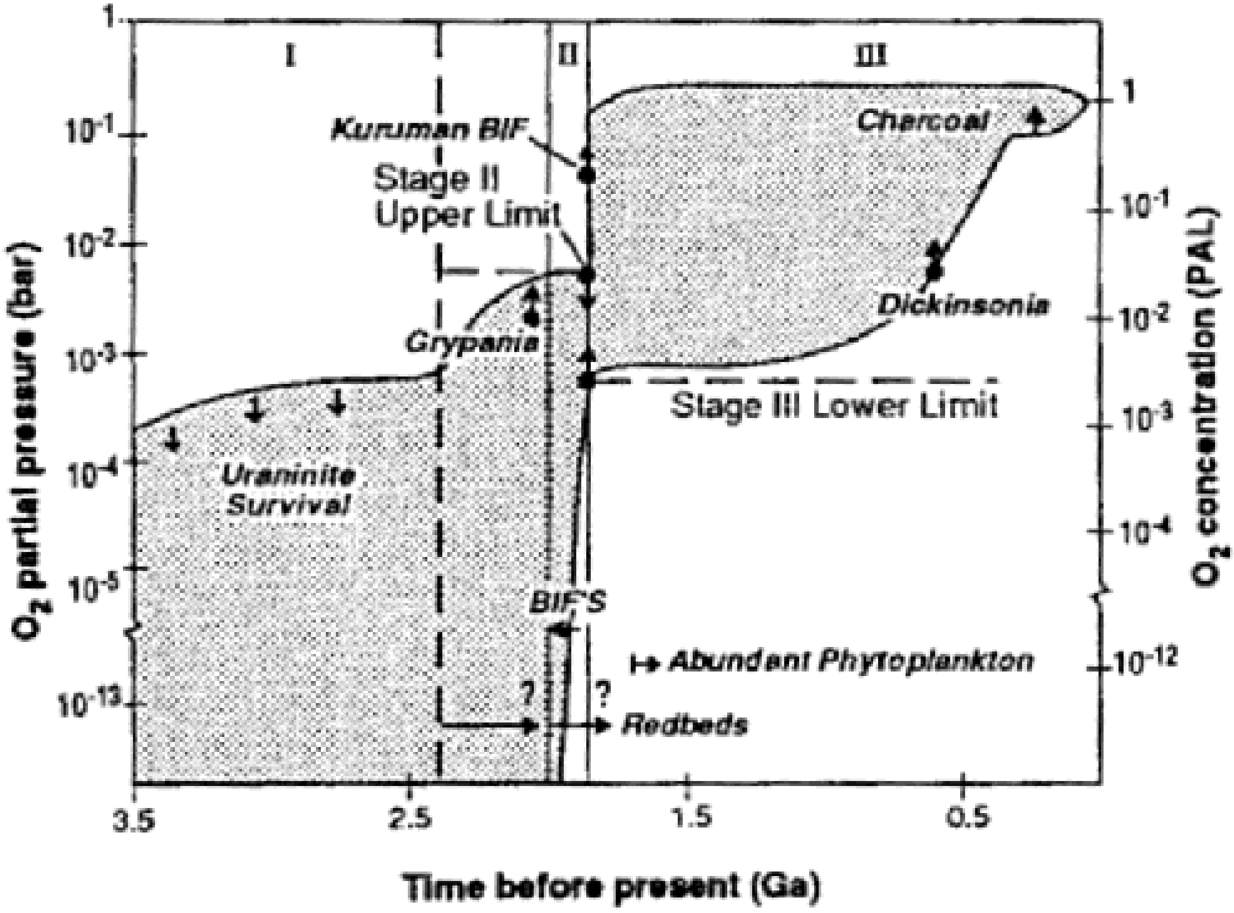
Habitability

- Surface life on a planet requires liquid water to be present. In addition, if the planet is to have substantial chemical modification by life, there needs to be an atmosphere to retain some gases and allow others to escape.
- Water at temperatures where it is liquid at modest pressures has a high enough vapor pressure for its spectral features to show, though the band strength varies linearly with atmospheric pressure.
- Oxygen is the chief ingredient of our atmosphere to have been made abundant by life processes. In the form of ozone, it provides heating in the upper atmosphere.
- In addition to the strength of the 9.7 µm ozone band, the presence of ozone is seen indirectly in the 15.6 µm carbon dioxide band having a central inversion.

Oxygen as a Biomarker

- Oxygen and Ozone spectral features are the best biomarkers because these gases are so reactive that their presence either implies current formation, or that they have no access to rocks. False positives to be excluded are Venus in runaway phase, and a giant ice-covered Mars.
- If we can see a feature at least 1/2 current terrestrial feature in size that implies that the molecule was no less than 1/4 its current abundance (for 1 atmos. pressure). For oxygen the time it was this high is between 0.4 and 1.9 billion years ago.
- For ozone this implies that the oxygen was no less than 10^{-4} of its current abundance. That is, it could be detected from 1.9 to > 3.5 billion years ago.

Oxygen History (Kasting)



Wavelength Regions Considered

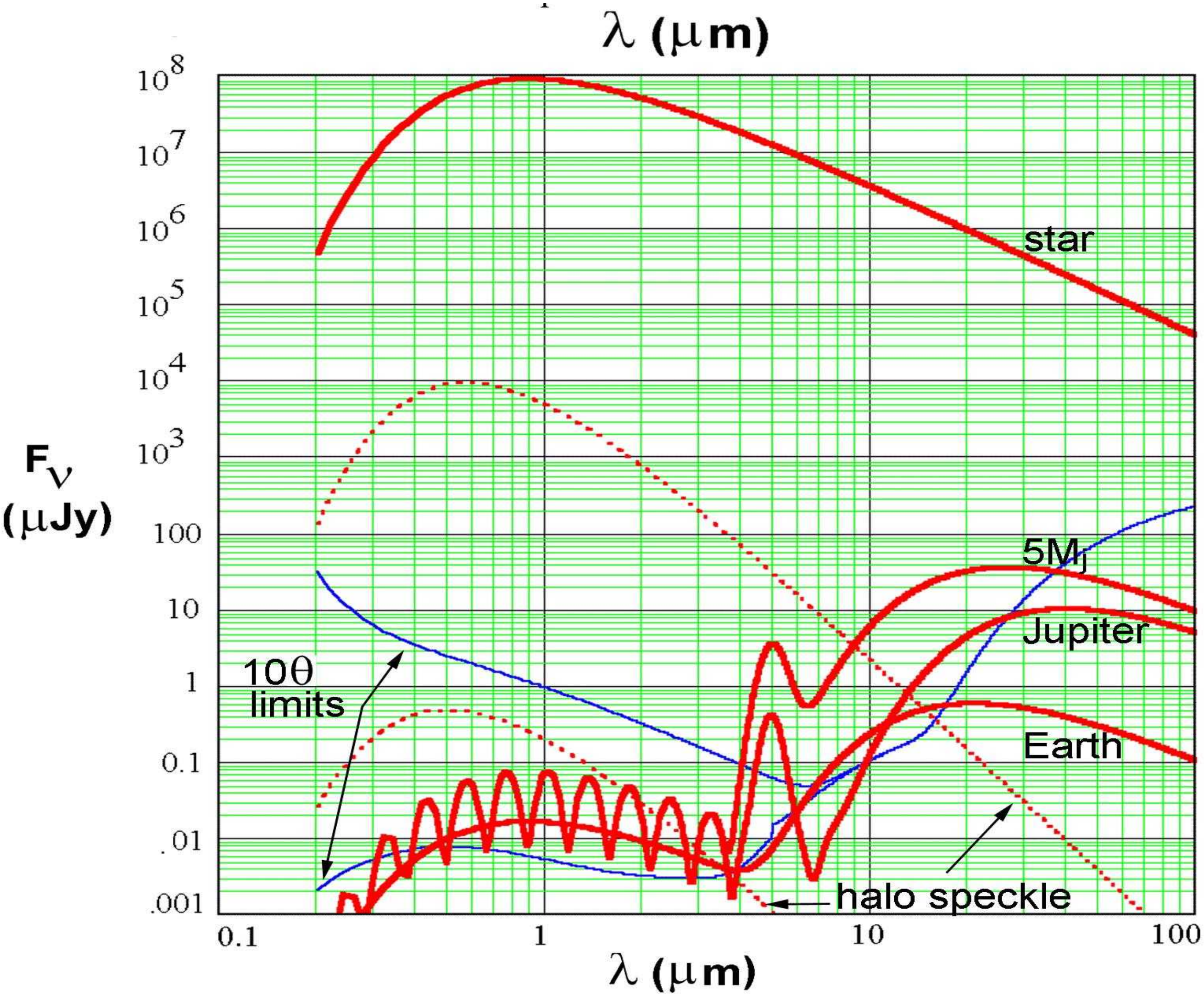
• Visible/far-red	Wavelengths in the range 500 nm - 1 mm.
• Near IR	Wavelengths from 2-4 μm
• Mid IR	Wavelengths from 7-30 μm
• Radio	Wavelengths from 5-14 mm

Comments: The region from 30 μm to 5 mm is a region where water has a high opacity, and it will be difficult to see other molecules.

The region 5-7 μm is mostly filled by the 6.3 μm water band. We did not find reasons to focus on it.

Wavelength Dependence of Star-Planet Contrast

Star and Planets at 8 pc



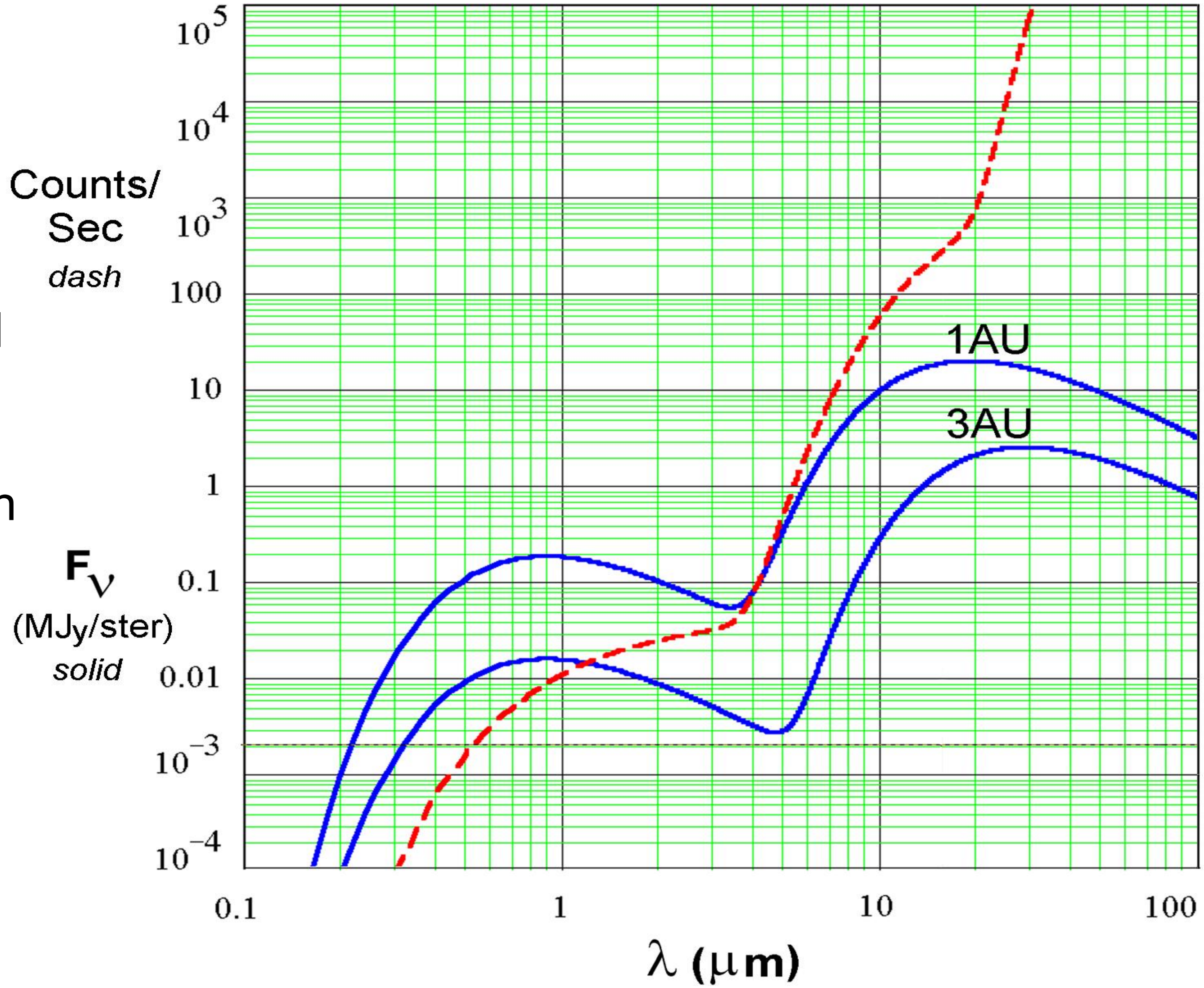
Planet-Star Contrast

0.5-4 μm	5×10^9
7 μm	10^8
10 μm	1.2×10^7
20 μm	1.7×10^6
10 μm	2×10^5

- Note the rapid change of star-to-planet ratio from 7-20 μm.
- Fluctuation of residual star signal must be reduced to allow high signal-to-noise for planet.
- The 10 μm number does not allow for the greenhouse increase of 8-13 μm fluxes.

Zodiacal Fluxes

Zodiacal Glow & Thermal Emission



Star-Zodiacal Glow Contrast

Contrast varies with star distance and aperture size. Here we consider the star to be at 16pc, and a set of four 3.5m apertures and consider the flux within the star diffraction core.

1 µm	9×10^{10}
4 µm	3×10^{9}
7 µm	9×10^{5}
10 µm	6×10^{4}
20 µm	2×10^{3}
30 µm	5×10^{2}

The zodiacal dust is assumed transparent at 10 µm

These numbers define a lower limit to the nulling factor needed at each wavelength. Otherwise residual star-leak photon noise will dominate.

How Chopping and High Frequency Nulling Adjustment Helps

If the phase is adjusted twice per second, there will be ~170,000 nulling measures per day. Let each adjustment have an rms error 1/3 of the peak allowed star-leak. Then the error after 1 day of observations = 8×10^{-4} of the star leak.

Using viewgraph #15, the nulling must be at least 900,000 at 7 µm and 60,000 at 10 µm.

If random errors of the star null set the limiting noise, the noise will be 9×10^{-10} of the star signal at 7 µm and 1.3×10^{-8} at 10 µm.

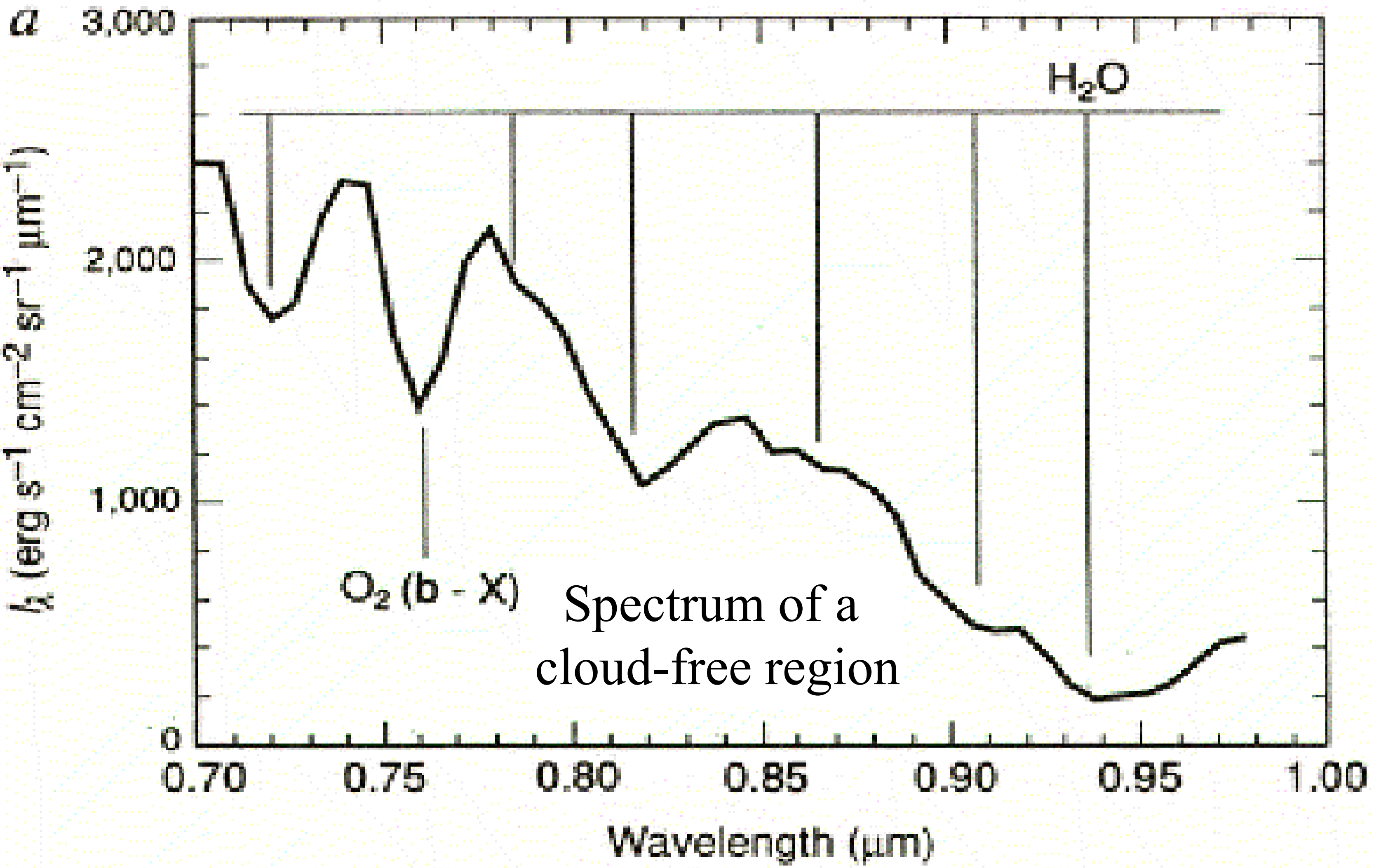
Using viewgraph #13, this **noise level will permit a planet signal/noise ~10 in 1 day of observation**. For shorter observations, and bright stars, the noise may not diminish much.

To avoid thermal drift noise, we make the chop cycle ABBA, and as high a frequency as possible. Nulling measure/adjust time step is shorter than the chop cycle e.g. 0.5 seconds versus 8 seconds.

Conclusion: Chopping is absolutely essential! We are even pushing nulling drifts let alone thermal drifts.

Visible/Far-Red

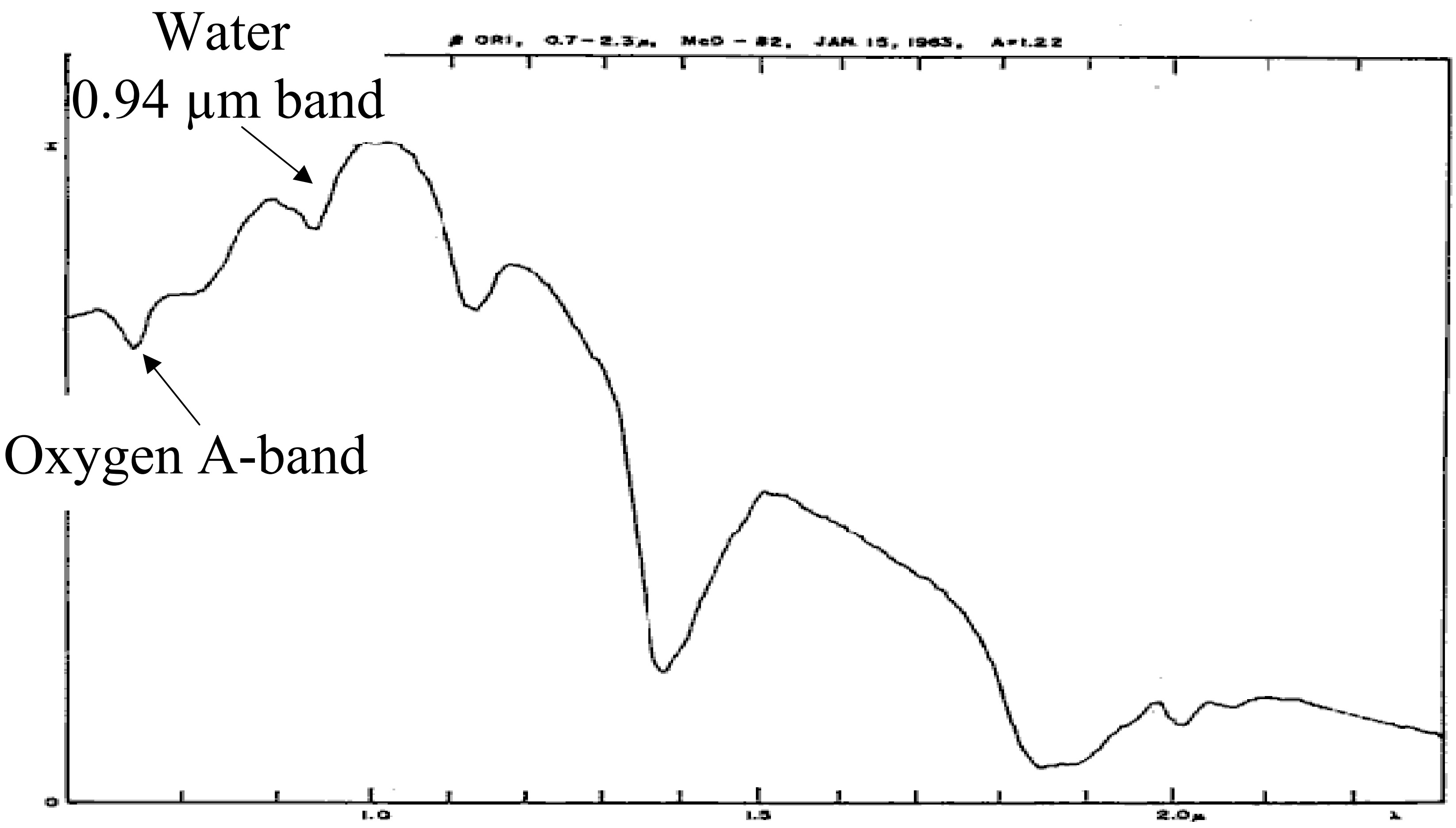
Earth Reflection Spectrum from Sagan et al. 1993



Spectrum of a cloud-free region

Spectrum of Terrestrial Oxygen and Water Superposed on the Spectrum of Rigel

~1.5mm ppt H2O (from Kuiper 1963)



Water
0.94 μm band

Oxygen A-band

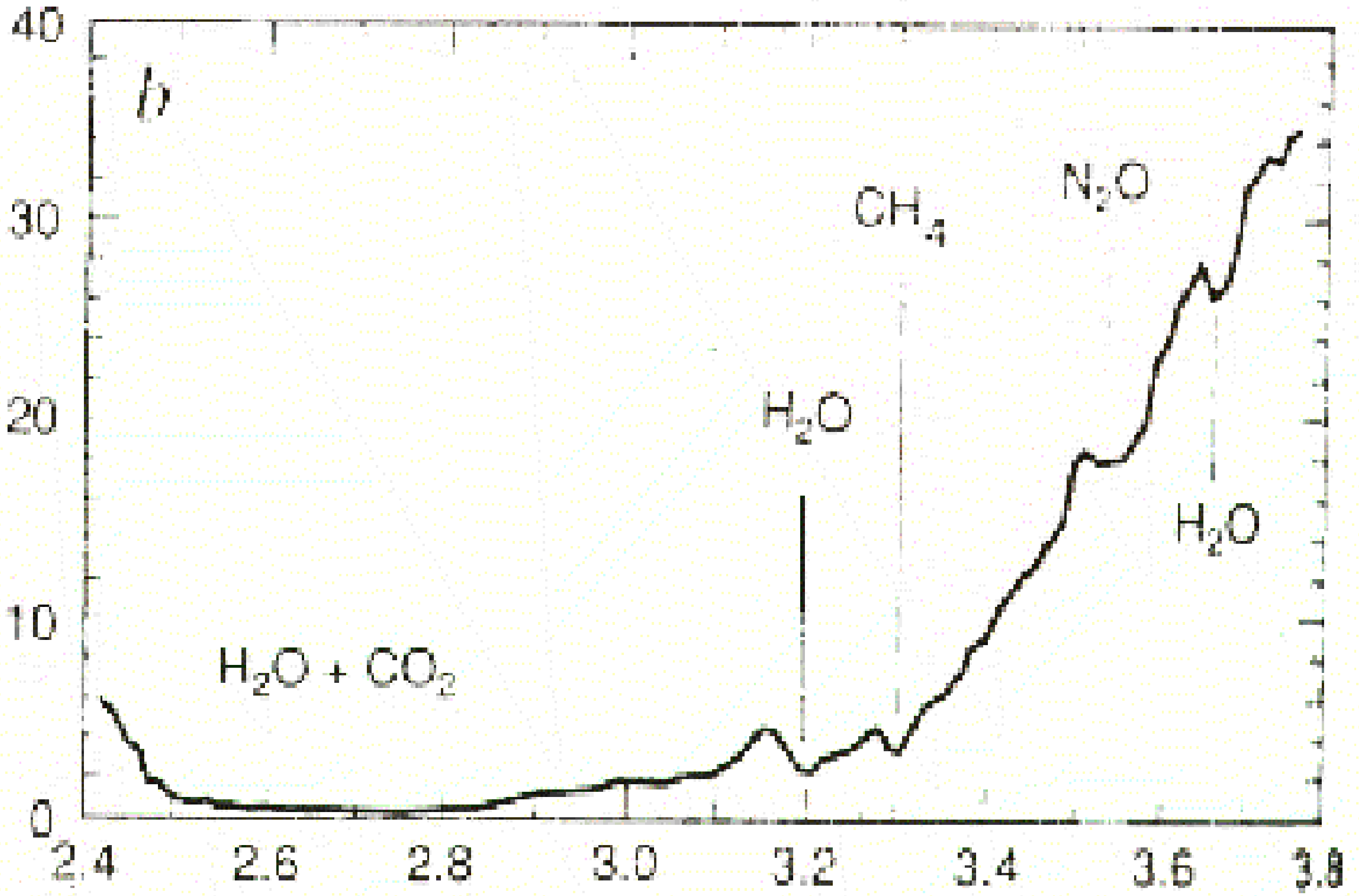
Visible/Near-Red 1

- Shows water, indicating habitability (0.94 µm)
- Shows oxygen (0.76 µm), a first rank biomarker.
- Oxygen band is narrow needing R~200.
- Contrast of $5x10^9$ is the major challenge.
- Zodiacal glow photon noise is not important.
- Temperature and planet size can only crudely be estimated by assuming an albedo. In this region water is a very poor indicator of oceans (vapor pressure varies rapidly with temperature, which is poorly known).

Note: Although Sagan et al. consider chlorophyll absorption a biomarker for spatially resolved earth, there is no good reason for assuming that a broad absorption at visible wavelengths is organic rather than inorganic for an unresolved exo-planet.

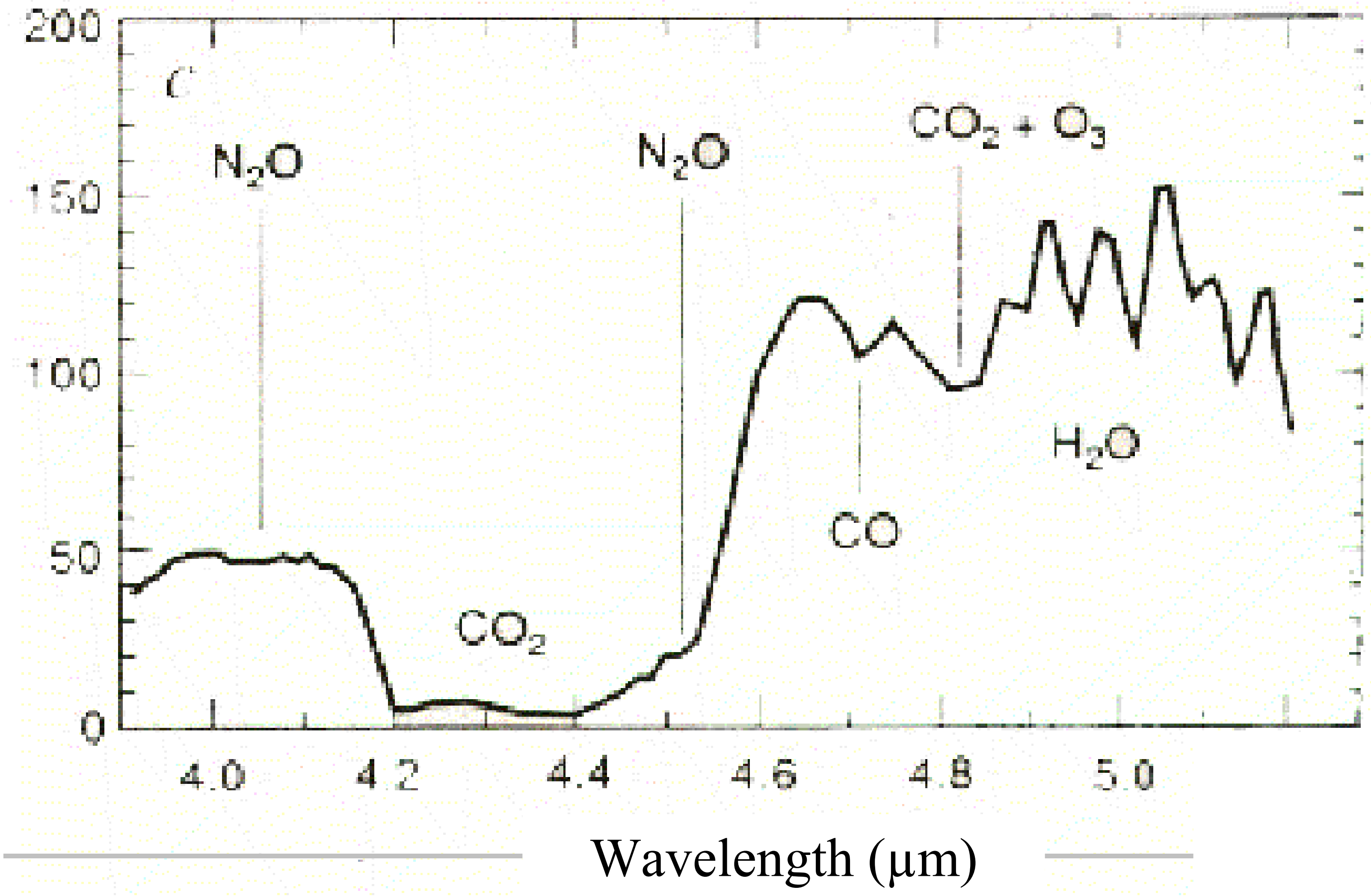
Near IR 1

Earth Reflection Spectrum from Sagan et al



Near IR 2

Earth Reflection Spectrum from Sagan et al



Near IR 3

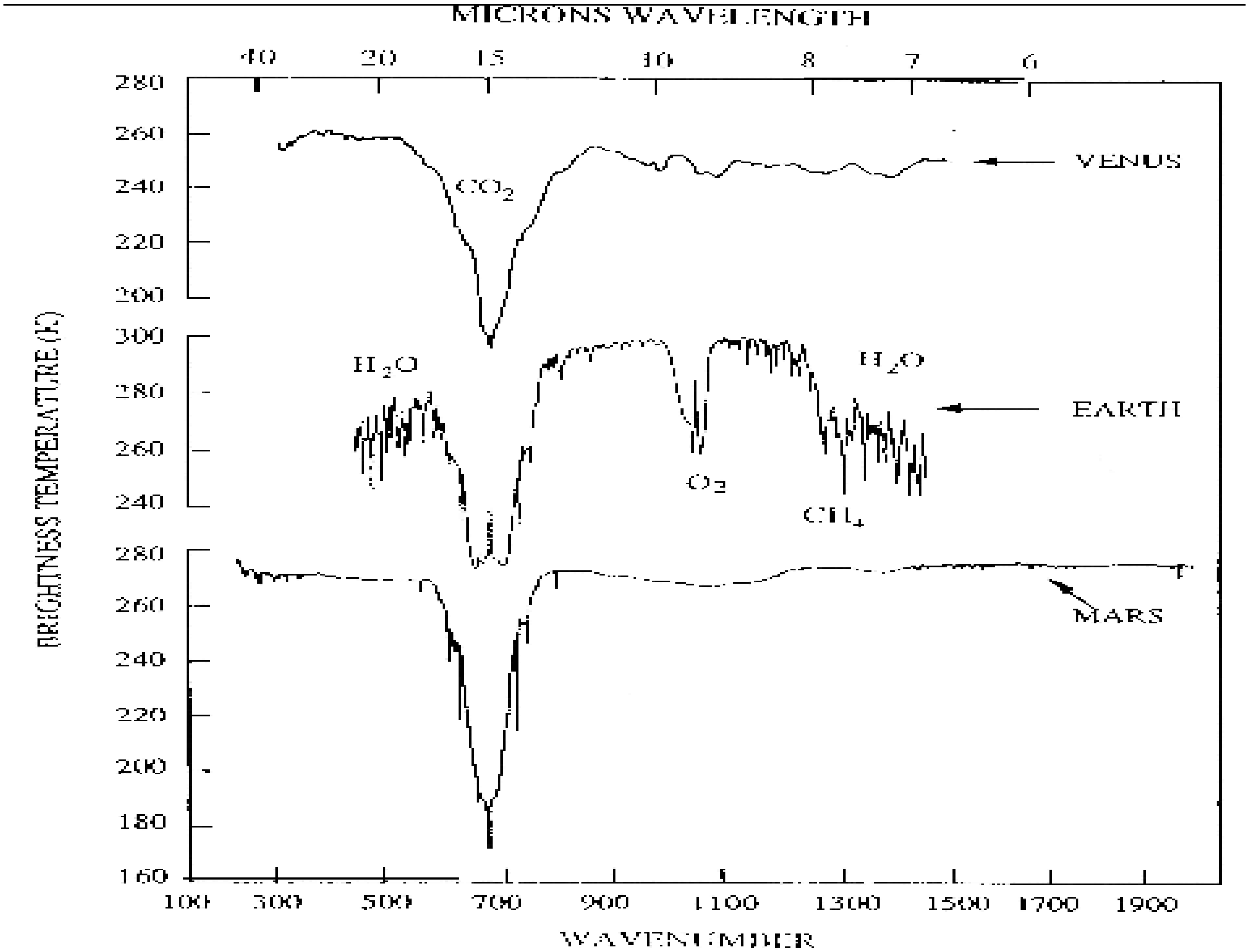
- The only first rank biomarker in this range is ozone at 4.9 µm which is confused with CO_2 and therefore uninterpretable.

- The special feature of this spectral region is CH_4 at 3.3 µm. This seems to be the most clearcut of the methane features.

- CO, useful for comparison with CO_2 is also available at 4.7 µm.

- This is NOT a candidate TPF spectral region. It is potentially a region for Life Finder, because it adds information that clarifies that from other spectral regions.

Mid IR #1


MICRONS WAVELENGTH
40
20
15
10
8
7
6
280
260
240
220
200
300
280
260
240
280
260
240
220
200
180
160
BRIGHTNESS TEMPERATURE (K)
CO_2
VENUS
H_2O
H_2O
EARTH
O_3
CH_4
MARS
100
300
500
700
900
1100
1300
1500
1700
1900
WAVENUMBER

Mid IR #2

- Water shows both at 7-8 and 17-30 µm. BUT nulling at 7 µm needs 1 nm precision. At 17 µm it needs 13.5 nm precision
- Shows ozone (9.7 µm), a first rank biomarker.
- Ozone band is moderately broad needing R~20, and because the ozone is high in the atmosphere, its measure is relatively insensitive to cloud. Band visible for 45-83% of Earth history.
- Zodiacal glow photon noise sets the limit to observations.
- Temperature of planet can be estimated by the spectral shape from 8-13 µm.
- CO_2 and H_2O abundances can be compared, and contrasted with Earth.
- Core of CO_2 band confirms the ozone identification by showing the stratospheric temperature inversion even at low resolution.
- If water abundance is low, CH_4 may be seen at 7.65 µm.

Millimeter Wave Lines

- H_2O is a broad unsaturated line at 13.5 mm.
- Oxygen is a broad saturated line at 5.5 mm.
- From H_2O we can extract separately the broadening pressure and the amount of water.
- The observations are unaffected by cloud.
- The abundance of oxygen can be obtained.
- The fraction of non-oxygen gas causing the atmospheric pressure can be found.
- This spectral region can give a lower limit to the temperature by assuming that the water is at saturation pressure.
- Like the visible, the oxygen may only be present in the later stages of a planet’s life development

Requirements and Science Conclusions

- The science would suggest starting with a **less ambitious mission** because the nature of the regions close around stars is so unknown. And the knowledge of the objects and the technology need to proceed together.
- The required wavelength range **7-17μm** should be changed to **8.5-20μm**. And the region 8.5-9.2 microns should only be used to define the short wavelength side of the ozone feature.
- The wavelength regions in order of decreasing science value for a first flight are mm wave : mid IR : Optical : near IR. However the mm wave study will be found totally impractical for the 21st century. This leaves the **mid IR** as the **preferred** region.