LUVOIR 3rd Face-to-Face STDT Meeting

New Haven, CT
Nov 9 – 10, 2016
Talk slides available at http://asd.gsfc.nasa.gov/luvoir/events/

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High-Level Meeting Summary

Day 1 (Nov 9)

During the 1st day of the meeting, we started with updates from the four instrument teams.

1. Coronagraph (Laurent Pueyo)
2. LUMOS UV instrument (Kevin France)
3. High-Definition Imager (Marc Postman)
4. O/NIR Spectrograph (Courtney Dressing)

Marc Ferrari spoke about a complimentary UV instrument that will be studied by CNES and a consortium of other European organizations. This instrument will provide new capability in high-resolution spectropolarimetry. It will fill one of the empty LUVOIR instrument bays. The science & technical case for this instrument will appear in a separate section of the reports, to avoid being charged for the instrument during mission costing.

Jason Tumlinson gave an update on and demo of the LUVOIR simulation tools, which are coming along nicely. In particular, there have been a number of improvements in the coronagraphic spectroscopy simulator, thanks to Giada Arney. Try the tools here: http://www.jt-astro.science/luvoir.html.

We then heard about the science cases that drive aperture size for Cosmic Origins (John O'Meara), Exoplanets (Chris Stark & Mark Marley), and Solar System (Walt Harris). New results on exoplanet direct observation yields from Chris Stark were shown.

After lunch, Matt Bolcar reminded us of the features of different telescope designs (e.g. three-mirror antiastigmats, Ritchy-Chritien). He also refreshed our memory on what aperture sizes are likely to fit in which launch vehicles. The largest aperture that fits into an SLS launch vehicle with an 8.4-m fairing is ~ 16-m in diameter. The largest aperture that fits into an existing 5-m launch fairing is ~ 9-m. The 5-m fairing is highly likely to be available in the 2030s, as it's needed by the Dept. of Defense.

Figure 1: Word cloud from 3rd LUVOIR STDT Meeting

Aki Roberge presented a recap of the strategy and risk considerations that we heard about in STDT telecons over the last two months. Her final take-away thoughts were …

- Don't defeat ourselves with low expectations.
- But remain flexible to change, new knowledge, and uncertain futures.
    - Be adaptable and have contingency plans.
- Our goal is to convince ourselves and the community that LUVOIR is possible and worth it.

Next came a stimulating 1-hr group discussion to define the aperture size options for the STDT to chose from. Assembly in space of very large apertures was considered, but tabled. The final options were: 16-m, 12-m, and 9-m (or whatever fits into a 5-m fairing). The first aperture chosen for study was ~ 16-m. The second aperture chosen for study was ~ 9-m.

We ended the day with a discussion of communications matters. An outline for 50-min talk available on Google Drive (in LUVOIR_STDT / Communication folder) – comments welcome. All STDT members asked to provide 1 pretty slide on their favorite science case. Put it in the LUVOIR_STDT / Communication / Miscellaneous / Single_Science_Slides folder on the Google Drive. If you need slick new graphics, send a request to Shawn Domagal-Goldman.

There was some discussion of whether we need a new name for the mission. Apparently, the LUVOIR name isn't popular in some circles. Finally, there was brief discussion of preparation for the joint LUVOIR/HabEx day. The general goals are to 1) become familiar with what each team is doing, 2) establish congenial collaboration on common science & tech areas, and 3) begin discussions to ensure consistency between two studies.

Day 2 (Nov 10)

During the 2nd day of the meeting, we were in joint session with the HabEx STDT. We began with overviews of both studies, which covered overall mission philosophy, science cases, instruments & mission architectures, and the study plan & schedule. Britney Schmidt gave a talk on Solar System science, which has not yet been extensively discussed in the HabEx study.

We then heard a detailed presentation from Dimitri Mawet, Laurent Pueyo, and Gareth Ruane on new results from the "Segmented Coronagraphy Design and Analysis" study. New designs for coronagraphs compatible with segmented primary apertures have been developed. There are Apodized Pupil Lyot Coronagraph designs compatible with segmented, on-axis (obscured) telescopes. Vector Vortex Coronagraph designs compatible with segmented, off-axis (un-obscured) telescopes have been created as well, though more work is needed to evaluate their performance with on-axis telescopes. Furthermore, the Charge 6 Vector Vortex coronagraph shows very promising insensitivity to low-order wavefront errors, possibly relaxing telescope stability requirements by ~ 1 – 2 orders of magnitude. If these results stand up to further scrutiny, it would be a major breakthrough in enabling a large exoplanet direct imaging mission.

At the end of the same presentation, Ji Wang spoke on new simulations of exoplanet direct spectroscopy using coronagraphy combined with the high-dispersion template matching technique. Combining the two observational techniques shows some promise for relaxing the requirements for exoplanet direct observations (by up to 1 – 2 orders of magnitude in contrast). Including detector noise and speckle chromatic noise, the optimal spectral resolution appears to be R ~ 1000, although higher resolution is needed to detect CO_2. However, it was noted that this combined technique only provides relative abundances of molecules.

After lunch, Matt Bolcar spoke on UV coatings, polarization, and coronagraphy. Sensitivity in the UV requires coated aluminum primary and secondary mirrors, which were thought to be incompatible with high-contrast exoplanet imaging in the optical. New results from modeling and lab work show that is not the case. Polarization-induced aberration in coronagraph imaging is less with aluminum primary and secondary mirrors than silver ones over most wavelengths of interest. This is excellent news for compatibility of exoplanet direct observations and UV general astrophysics.

In the afternoon, the group separated into five breakout sessions.

A. General Astrophysics
B. Measuring Planet Masses
C. Exoplanet Yield Calculations and Assumptions

D. Exoplanet Characterization
E. Technology

An excellent start was made on achieving consistent input assumptions and science metrics for both LUVOIR and HabEx. Researchers are homing in on the frequency of habitable exoplanets (η_{Earth}), although factor of ~ 2 uncertainties remain. Considering planets with radii between 1.0 – 1.5 Earth-radii, estimates range from ~ 14% – 30%. Including smaller planets down to Mars-size increases the estimates to ~ 40% – 100%. Obviously, the exact definition of a habitable planet is a major factor in deciding the frequency. This led to a stimulating discussion in the Characterization breakout about what constitutes a long-term habitable planet.

The Characterization breakout also identified a number of important measurements for understanding a planet's climate, including mass, ocean detection, surface mapping, and spectral coverage over a large wavelength range. We need to define a strategy for a sequence of exoplanet observations of increasing depth (simple observation on many targets, filtering down to observations of greater complexity on the most promising ones).

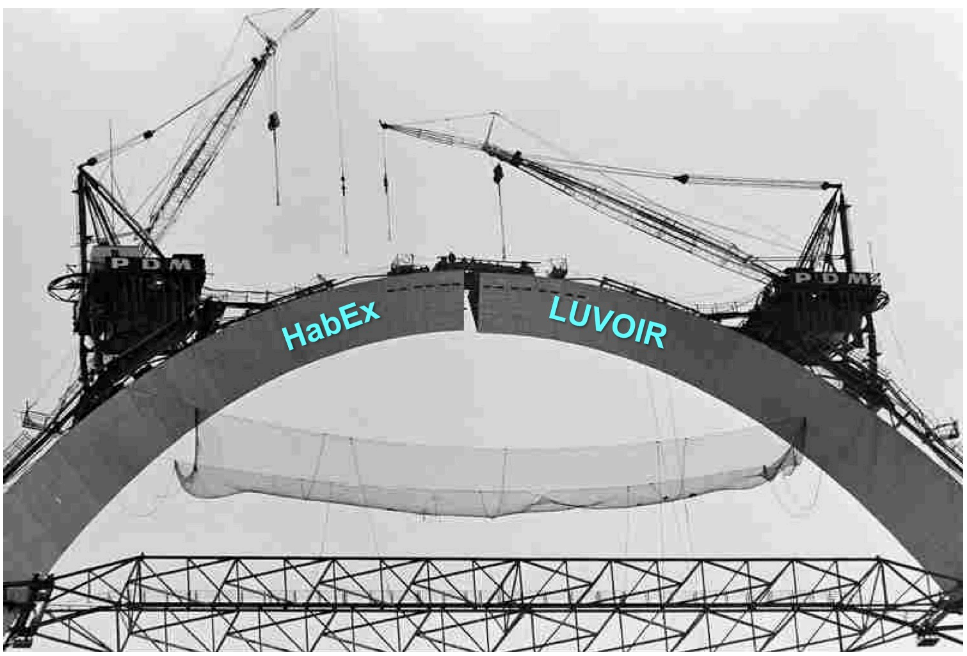

Figure 2: The Gateway Arch in Saint Louis. On completion of the east and west spans, it was found that they did not correctly meet in the middle. Adjustments had to be made to fit the keystone into the arch – a fate to avoid with the HabEx and LUVOIR studies.

After breakout reports, we had a discussion on how LUVOIR and HabEx should work together in future, led by Scott Gaudi and Aki Roberge. If LUVOIR and HabEx are envisaged as spanning a spectrum of missions, we want to "meet in the middle" upon interpolation (Figure 2). At the least, we should 1) not contradict each other and 2) reconcile our science, technology, risks and costs. There might be a possibility of a limited joint study (with additional funding) to interpolate between the small end of LUVOIR and the large end of HabEx. We had a stimulating joint discussion on mission costs. It was suggested we create joint slides on technical challenges and cost, in addition to the already-created joint slide on the "Difference between LUVOIR and HabEx", which focuses on science goals. Thus ended a very interesting and productive meeting.

Detailed Minutes

Day 1 (Wednesday Nov 9, 2016) – LUVOIR team only

Brad Peterson & Debra Fischer: Welcome. Some words about the election, acknowledging the mood in the room is low. Shawn Domagal-Goldman also says a few words.

Debra: We need to stay focused on the task on hand to prepare for the decadal survey.

Brad: We'll have to make trades eventually but they aren't final until we come up with a final document. We need to identify difficult tasks. Change mission impossible to mission possible.

Instrument Updates

Coronagraph (Laurent Pueyo)

- Open questions:
  - What bandpasses and resolution?
  - What are planet yields and how to increase them?
  - What is the required wavefront stability and how to achieve it?
  - What do we need to do for initial detection? It is hard to disentangle confusion between planets and background sources with just photometry.
- Shows GPI spectra.
- Resolution and bandpasses:
  - Architecture A: IFU + high res spectrograph?
  - Architecture B: IFU + imager?
  - How many parallel channels? If you do everything in one shot, you increase your yield. We need bandpass and resolution from exoplanet working group and from that we have to push coronagraph tech.
- Yields:
  - Chris Stark published his yields papers before we had any designs.
  - So far we have tech that will fly on WFIRST. How do we push the performance?
  - Segmented Coronagraph Design and Analysis (SCDA) study is examining different possible coronagraphs for segmented telescope apertures.
  - Apodized Pupil Lyot Coronagraph (APLC) design study is running many simulations on Discover supercluster to figure out optimal designs. Through brute force parameter search, arrive back at Chris's yields.
  - Vector Vortex coronagraph team developing lots of analytical solutions to take care of center of FOV. Charge 6 design for segmented off-axis telescope appears remarkably insensitive to wavefront error. Impact of central obscuration (on-axis telescope) to be studied.
  - For 12 m off-axis segmented, predicted ExoEarth yield is 2-8.
  - Contrast is degraded when central star is resolved

Brad: How many stars are we expecting to resolve?

Chris Stark: No, partially resolved. Fraction of lambda/D.

Brad: I thought we were suddenly talking about a much larger telescope.

Chris: This is 1st time we included impact of finite stellar diameter. But this only matters for stars closer than about 5 pc.

Brad: Keep in mind a good section of audience doesn't know anything about coronagraphy but we're anxious to learn.

Laurent:

- Yield close to expected from Stark et al. 2015.
- Moving forward quickly, lots of telecons will happen to discuss number of parallel channels, etc.

Daniela Calzetti: When you mention yield, what timescale?

Chris: Yield over two years of a five-year mission

Aki Roberge: For APLC, you were getting high yields with on-axis telescopes?

Laurent: These designs include constraints for the little bit of star that's not on-axis. We include finite stellar size.

Chris: Only place to go from here is up. Aperture shows hex design is filled out to edge on slides, but aperture is actually jagged around edge. Hex aperture has a penalty because it's not a full aperture. We will redo these calculations.

Aki: If I can sum up, looks like we have viable designs for on- and off-axis telescopes at the moment.

Mark Marley: Aberration sensitivity analysis for APLC?

Laurent: Lots done for Gemini Planet Imager. We've done our own in-house but not yet published. We need to do our homework on this.

Matt Bolcar: Discussion of outer working angle (OWA) and field-of-view (FOV)?

Laurent: Nothing about OWA and FOV. I think we will make educated guesses about what we can do.

Brad: We need to move on now.

UV Instrument – LUMOS (Kevin France)

- Multi channel instrument. High-resolution point source spectrograph (echelle). Multi-object imaging spectrograph with medium- and low-resolution modes. NUV IFU and NUV imaging mode under discussion.
- Short wavelength cutoff: 100 nm with stretch goal of 90 nm.
- Multi object spectrograph: notional idea is 2.4' x 1.3' FOV, with angular resolution of 50 mas.
- Aki asked me to emphasize that all of the technologies in the LUMOS design are things that we can build today. 4 currently funded rocket projects are doing work related to LUMOS.
- We've turned in the Optical Design Lab (ODL) and Instrument Design Lab (IDL) input sheets, as well as a preliminary instrument design.
- Have to extend effective focal length.
- Pushing down a factor of 10-100 fainter than previous and existing UV instruments = "awesome"
- Jason Tumlinson's LUMOS simulator has lots of template spectra for quasars, stars, etc.
- In summary, we have a working instrument design, requirements laid out, notional effective area and resolution curves. "Very feasible instrument to build."

Daniela: What are technical difficulties to go to 20 mas resolution?

Kevin: Telescope needs to be optimized to be diffraction limited at a shorter wavelength.

Brad: Not clear to me what instrument layout is. Where is coronagraph relative to LUMOS?

Kevin: That's something we should talk about. We assume broad focal plane so instruments can share (the way HST works). LUMOS would be slightly offset from center of field. Notional design doesn't actively take this into account yet.

Matt Bolcar: I'll talk about his later too.

Brad: What is physical size of box?

Someone (Matt Bolcar?): 2 meters by 1 meter

Lee Feinberg: Anything we should cover in tech working group?

Kevin: UV coatings and microshutters.

High-Definition Imager – HDI (Marc Postman)

- HDI science team includes many members not on STDT. Lots of expertise here.
- "Ultra-faint, ultraviolet, ultra-precise, ultra-high resolution"

- Considering sub-microarcsec astrometry capability. Would enable astrometric detection of 100s of exoEarths and measure masses.
- Probably need a separate NIR channel.
- 4 to 6 arcmin FOV. Nyquist sampled.
- No space-based detector ever flown that's actually been Nyquist sampled. Have had to dither at these wavelengths. Recovers some of the resolution but introduces artifacts when you co-add images. These artifacts go away if detector is truly Nyquist sampled.
- 0.2 – 1.8 um bandpass (stretch 0.2 – 2.5 um)
- Still assuming diffraction limited down to 500 nm but specify Nyquist sampling down to 400 nm (stretch 200 nm).
- 10 mas spatial resolution if diffraction limited at 500 nm.

Brad: This sounds like magic to me.

Marc: In space you're very stable. Still working on this.

- Solar system wants high dynamic range, tolerance to very bright sources.
- Solar blind performance: UV imaging needs high red light rejection.
- Very high QE devices being studied at photonics lab for NUV and visible. 40% QE. Degradation at red end because these are thin devices. Need to think about if we want this range.
- Biggest tech challenge is number of pixels (multi-gigapixel desired).
- Special modes: high precision astrometry mode, high-speed photometry mode.
- Detector development in progress. Again, emphasis on number of pixels.

Someone asks about low-resolution GRISM modes. Lots of agreement.

Marc: Agreed.

Avi Mandell: Simultaneous coverage across these wavelengths? Or separate?

Marc: Not sure.

Someone asked about transit spectroscopy.

Marc: We haven't yet discussed that option.

Courtney Dressing: Speaking of transits, possible to cool instrument to go redder?

Marc: We made a stretch goal for 2.5 um. Warm HST had K band mode and "still beat the pants off the ground." Don't know where we're pushing boundaries yet.

Aki: How do you calibrate to 1000th of pixel for high-precision astrometry? Laser calibration system (basically a small interferometer) to detect pixel sensitivity variations. Mike Shao has demonstrated in lab, right?

Marc: Yes, I can circulate results where he shows lab demo.

Aki: Pixel sensitivity variations are currently limiting factor for transit observations. If detector is well calibrated for astrometry, should be amazingly awesome for transits. But that's a bonus.

Marc: Also exciting is galaxy proper motion and astrometric measurements of exoEarths.

Aki: Key function of this mode is not finding targets. It's measuring masses.

Marc: Week of integration time to look at 100-150 stars for exoEarths. Not huge commitment. Then you have your target list for direct observations with coronagraph.

Debra: Doesn't astrometry have to map out orbital period?

Aki: To measure mass you do want whole orbit. We could detect a planet with fraction of orbit.

Debra: We've never done that before.

Aki: Nobody has ever built an instrument like this before.

Marc: Well, at least you didn't all fall off your seats when I talked about gigapixels.

Optical / Near-IR Spectrograph (Courtney Dressing)

- If you want to suggest a new name, let me know.
- Can do expansion of universe, black holes, distribution of black holes, etc.
- On SS side, perhaps we can characterize planet 9, surface processes, Titan, comets.
- On exoplanet side: host star characterization, masses of planets, etc.
- FOV not biggest driver. It's resolution.
- High spatial resolution (0.008" res has Britney excited)
- Could do bright targets in transmission out to 5 microns.
- Fixed slits + IFU
- Please find me at breaks, dinner if you have input.
- Is FOV a concern for you? Are other science cases for other resolutions? What do you want to do with O/NIRS that you can't do with other instruments?
- Matteo Brogi working with Mike Line and thinking about template matching.
- Still looking for more team members. Looking at designs from past instruments. Writing simulations with Geronimo Villanueva's code and Chas Beichman's code.

Daniela: Add low-res star formation?

(Didn't catch response)

Ravi: Question online: Why magnetic fields of hot stars?

Courtney: That's from document I took it from but it could be any stars. This is a subset of science you can do, do not a comprehensive list.

Bekki Dawson: How much would you lose if you can't go to lowest resolution you want?

Courtney: It's a question if you can get simultaneous coverage. (Missed part of answer)

Debra: Noticed you're using microshutter arrays. Are these stable?

Kevin: We use them in UV. They use microshutters out to 5 um on NIRSPEC.

Overview of CNES instrument contribution (Marc Ferrari)

- CNES willing to support participation of French space laboratories in LUVOIR study.
- Continuation of NASA/CNES collaboration on UV missions.
- ARAGO mission concept:
  - Phase 0 study funded by CNES.
  - UV and visible high-res spectropolarimeter
  - Observations of all kinds of stars. 4 year mission with full sky observations.
  - 1.3-m Cassegrain telescope
- UV imager/spectrograph – science capabilities
  - Wide field imaging (typical 5'x5')
  - Low to moderate spectral resolution (100-5000)
- Two complimentary UV instruments. Need to coordinate CNES study with one led by Kevin France.
- Upcoming actions: 1st meeting of instrument definition group (Dec 2016). Coordinate activities with STDT and GSFC teams on UV instruments. French workshop on LUVOIR. Engage discussion with ESA.

Aki: Very pleased about this collaboration. I have a little guidance about easier ways to do it. Talking with HQ people, the easiest way to avoid trouble with ITAR is if CNES takes whole instrument and studies on its own and we interface telescope parameters and box size.

Marc: That's on tech design side.

Aki: If we want to avoid getting charged for this instrument on our total mission tab by Aerospace Corp, best way is to put whole instrument with science and technical case into one clean report section for CNES. Otherwise, Aerospace will charge us and that will defeat point of international contribution. Also, I don't think we can put this instrument through the GSFC Design Center. We're out of money on our side. CNES cannot pay GSFC to use the Design Center. Ideally, you guys do your own version of that process and we plug it in afterwards.

Marc: We are planning our own design, yes.

Brad: What we propose at this point not set in stone. For budgetary reasons, let's keep instruments separate. Talk to LUMOS.

Kevin France: Great that French community excited for this, especially for spectral polarimetry. In terms of keeping things separate vs. overlap, I am concerned about tying in cosmic origins science into something that is an ESA contribution. If something complicates that, there could be a big piece of COS that LUVOIR can't do. Any interest in imaging polarimetry?

Marc: Spectral polarimetry is first thing. Imaging could be considered.

Simulation Tools Update (Jason Tumlinson)

- Online, there's a link in the Adobe Connect (http://www.jt-astro.science/luvoir.html)
- Eight tools right now.
- This is first live test of a bunch of people in same room using all at once. This will happen at the AAS splinter meeting. So if we see things grid to a halt, need to find a solution.
- LUVOIR Photometric ETC
  - Gives you SNR as a function of wavelength.
  - Sliders: aperture, exposure time, magnitude.
  - Want to expand to choice of tabs.
  - K band affected by thermal background that we included (assuming 280 K for telescope temp).
- LUMOS
  - Has selection of template spectra.
  - Sliders for magnitude, resolution, grating/setting, aperture, exposure time
- During session, server got killed for excessive resource usage. Clearly the server can't handle the load!
- Giada Arney demonstrates coronagraph noise model. Lots of new template spectra added, new detector noise parameters.

Cosmic Origins Aperture Drivers (John O'Meara)

- "It's kind of fun to do the impossible"
- Should compare total science programs holistically and bound by ultimate limited mission resource which is mission lifetime.

- Goal: Protoplanetary disk within 1 AU of central star. Need: Enough aperture to get to Hyades or beyond. Need large aperture.
- LUVOIR + LUMOS + O/NIRS for red giants and halo stars.
- Goal: Complete sample to 60 Mpc. Need: 34^{th} mag = 9+ meters
- To get nearby elliptical galaxies, need apertures > 8 m.
- Get more quasars than HST by factors of thousands.
- Lensed galaxies with HST = normal galaxies with LUVOIR. Can observe 100 pc-sized clumps.

Shawn: Does this curve turn over? (% clumps recovered vs. aperture diameter)

Jane Rigby: Curve turning over because it's a clump we had to have seen with Hubble using lensing.

Shawn: Real turnover but due to obs. bias?

Jane: Yeah that's why.

John: What do lensed galaxies look like with LUVOIR?

Jane: Well, that's super fun.

Daniela: Little surprised by how steep this curve goes.

Jane: I understand why it rolls over > 10 m (approaching resolution of HST with lensing).

John: Part of this is being dominated by bright blue stars.

Jane: The steepness is real.

Daniela: I'm a little surprised. Doesn't mean not correct.

Jane: Some of it is because we chose to use a real galaxy, only has 24 clumps with range of luminosity and size. This is real. But we've spent time staring at it and asking if there's something going on between 6- and 10-m? I don't think so.

- Dream measurement: Imaging of GCM. Main question is what is aperture for this. Something that you can observe in 3 hours with a 4-m, you get in 15 min with 10-m.
- With microshutter array, get all galaxies in array trivially. Count up galaxies on sky, there are 10000 galaxies (25^{th} mag) per square degree.
- Science at the Olber limit. You practically get to Olber's paradox. Every pixel is a galaxy.
- "LUVOIR + HDI: We'll do more in a day than you will all year."
- Direct distance to things in Virgo "boggles my mind."
- Resolution, sensitivity, and transformative science demands > 9 meters.

- All instruments can do revolutionary COR science.

Marc: We need to translate observation gains to scientific gains.

Aki: This is the point where I urge the COR working group to go back to the original template for science case documents.

Brad: Amount of integration time it takes is a good argument for aperture. It's "will you do this or will you not do this?"

Daniela: In addition to science questions, we should also compare with what will be launched or coming online? Proper motions are key arguments for 30-m imagers. We must compare to everything coming online for 10-15 years.

Jane: You're getting at what is unique?

Daniela: Yes.

Aki: I need to understand if this is an incremental gain or a transformative one.

Marc: I'm not a miracle worker.

Aki: This is on everybody.

10 Aperture Drivers for Exoplanets (Chris Stark)

- Why should LUVOIR STDT be thinking about a large LUVOIR?
- Larger aperture = greater exoEarth yields.
    - We need a powerful null result in search for life. If we don't see any signs of life, we still want to say something useful.
    - We should take a cue from physics colleagues (Tevatron vs. Large Hadron Collider) so that null result is still meaningful.
    - We can constrain f_life with different confidence levels.
- Must get past segmentation penalty.
    - For some coronagraphs, monolithic telescopes will have larger yields than their segmented counterparts.
    - Breakpoint where this occurs unknown.
- Large apertures potentially less sensitive to instrument degradation.
    - Can adapt target list to mission. Small apertures can't do that.
- More robust to astrophysical uncertainty.

Jane: Why smaller apertures sensitive to exozodi?

Chris: Not more sensitive. If exozodi level is 10x greater, it can cut your yield in half. Small number statistics.

Jane: It's just Doctor Poisson?

Chris: Yes.

Daniela: Measurements of exozodi?

Aki: Yes, Large Binocular Telescope Interferometer exozodi survey has started doing this, though would be nice if it was going faster. Should get down to 3-10 zodi level.

- Larger aperture provide shorter integration times (even though they observe more distant stars).
  - Smaller IWA -> brighter planets
  - In background limited regime, characterization time of planet goes as D^4.
  - Slide showing R = 70 spectrum of O_2 A band. Does NASA want to use this to claim signs of life? (Laughter because the plot doesn't look too impressive compared to R = 300 spectrum next to it.)
- Enables new kinds of exoplanet science.
  - Mapping planets, resolving circumplanetary material.
- Enable new exoplanet discovery techniques.
- Greater diversity of exoplanet host stars.
  - Smaller aperture skewed to earlier type stars. Almost no M stars.
  - Larger aperture gets M stars. Some overlap with future ground based ELTs.
- Greater diversity of exoplanets found.
  - Smaller apertures may not discover many Jupiters.
- Sample size.
  - Shows Sing et al. Hot Jupiter comparison spectra – all different. We need larger sample size for comparative planetology.
- Planet-planet confusion: overlapping "bird diagrams".
  - Exoplanets probabilistically found in different regions of separation vs. delta-mag space.
  - They overlapped lots of Bird diagrams for different targets. Greatest confusion for hot small planets at smaller semi-major axes.

Shawn: From an observational strategy standpoint, you could also try multi-band photometry to distinguish between planet types, instead of revisits. Three observations are about equal to dividing your observations into three bands. You can rule out cases like background sources and different planet types.

Chris: Question is which is more costly. Coronagraph wants to do multi-epoch imaging anyway.

Vikki Meadows: I'm not sure I totally agree with band photometry. It's like early red and blue KBOs. We may have to calibrate our colors with spectra in the end. Colors are so ambiguous. Colors are dangerous.

Chris: There's no color info in this at all.

Deeper dive on characterization drivers (Mark Marley)

- Main concern is going into NIR.
- Proterozoic Earth spectra: Importance of NIR bands to get CH_4 and water.
- NIR can distinguish false positives.
- With a 4-m telescope, you can only do a few planets in NIR. For example, with 2.4-m WFIRST, you can't get red spectra for a lot of bright Jovian planets due to IWA.
- Aperture helps you get into the NIR.
- WFIRST study says need SNR > 20 for useful abundance retrievals. (!) Need to have more efforts on doing retrievals.
- "Sweet spot" for exoplanets likely 12-15 m

Karl Stapelfeldt: Mini-Neptunes and larger planets also benefit from NIR.

Bekki: Regarding confusion plot (Chris's overlapping bird diagrams), is there intuitive way to understand why there's a region where there's a lot of confusion, and what are range of properties of planets in that region?

Chris: If you have a small IWA, you can easily detect Earths. But whenever you probe to smaller and smaller IWAs, you can fool yourself with smaller planets closer to star.

Someone: OWA a roll-off point between one method of detection and another?

Mark: To see debris disks, Jupiters at 5 AU, Saturns, etc., we really need large OWA.

Karl: I want to add we have an OWA for HZ planets that's small. We have another for giant planets. What if we only do giant planets in NIR where we have enough outer working angle to do them?

Vikki: On SNR > 20 on retrievals, is that because range of retrievals is so large it's physically meaningless?

Mark: Don't know radius and clouds. Start exploring large pieces of parameter space. LUVOIR will do better with large wavelength range compared to WFIRST. Lots of combinations of properties can give you same spectra (gravity, clouds, size, etc). Everybody is showing a metallicity vs. mass curve, but error bars on that plot are an order of magnitude.

Aki: For SNR = 20 for retrieval, did you constrain gravity based on knowing planet masses?

Mark: Even if you know planet masses from mass-radius relationship, there is uncertainty in radius. Community needs to do retrievals on these low-info spectra.

Aki: We've been assuming we must have the masses. How much does knowing the mass help?

Mark: It will help a lot. We need to quantify this.

Unknown: You need to know what object you're talking about.

Aki: We need to quantitatively say how much value there is in constraining the mass. With coronagraph spectra tool, download simulated data and start doing this.

Vikki: SNR to the base of the band? Continuum?

Mark: On continuum.

Vikki: Good. Almost no flux in bands would be tragic.

(Gap in transcript from 1 - 2pm because Giada had a telecon.)

Technical Considerations for Telescope Architectures and Launch Vehicles (Matt Bolcar)

- Going to study two aperture sizes.
- Discussion of launch vehicle accommodations.
  - Largest aperture in SLS 8.4-m fairing: ~ 16-m. Largest aperture in 5-m fairing: ~ 9 m.

Aki: Don't have to go up to 20-m to gain factors of 100 over HST.

Shawn: 20+ m telescope would be global/national priority, not just NASA priority. We have been commissioned to study a thing that can be the astrophysics priority.

- Test facility: need liquid N trial to do thermal balancing test.
- If assume room temp telescope, some testing performed in vacuum, in big cleanroom. These things have JWST heritage.

Jane: Even w/ room temp telescope, why need nitrogen?

Matt: Room temp telescope but within a cold shroud to simulate space.

- Existing vacuum vessel is not large enough to fit a 20-m telescope. Even 16-m is a challenge. Can't do 16-m w/ liquid N shroud. Can't do 12-m w/ helium shroud.

Nick Cowan: How much to build bigger facility?

Matt: There's another bigger facility, but it doesn't have clean rooms. $100 million for a new one.

Brad: Political capital to be gained by reusing existing facilities. Gives leverage.

- These space mirrors are nothing like ground mirrors. Picometer precision.
- SLS 1B/2B designations are everything below fairing. Difference is extra rocket booster and mass of fuel tank.
- SLS office says we can't go to Mars without a 10-m fairing. Decision of when to start 10-m fairing has not yet been made to make it. If country decides to go to Mars, we will need this rocket.

Dave Redding: Whatever we propose will be scalable.

- Is it worth the extra cost to make the telescope cold to get to NIR?
- On-axis vs. off-axis?
    - Does impact on exoplanet yield merit that additional cost driver?

Chris: If we go with assembly in space, does that have to be tested on ground?

Aki: Probably. How else will we know it will work?

Matt: Maybe we need to start testing at the sub-component level. That's really scary but that's where we need to go.

Marc Postman (?): Nobody did a ground test of the ISS.

Lee Feinberg (?): We make assumptions from each aperture. Maybe we can do a subscale thermal balance test. But for picometer stability, this is not the place to break the testing paradigm.

Brad: Time for coffee break.

Recap of strategy and risk considerations (Aki Roberge)

- Summary of previous telecons.
- In these telecons, we wanted a broad range of perspectives, but they haven't necessarily provided a huge amount of clarity. But we'll see …

1. Debra Emmons presentation on Aerospace Cost and Tech Evaluation (CATE)
    - Independent Cost Estimate (ICE).
    - Add three types of cost threats, where appropriate.
    - No surprise the CATE cost is likely higher than team estimate.
    - Potential available funding for strategic missions is $400-500 million annually.

- Tech risk approach: They want to know if you have a believable plan to deal with tech risks. They give your mission a risk color (blue to red).
- Aerospace recommended having multiple concepts for evaluation = why we will study two aperture sizes.
- Recommended lots of margin on launch vehicles. Understand that relying on a vehicle in development (SLS) will be assessed as a cost risk.
- Heritage / analogs matter.
- Red missions (most risky) rarely or never if ever get approved without modification or descope.

Marc Postman: For launch vehicles, did they say anything about relying on existing vehicle that may not exist in 20 years?

Bob Bitten (Aerospace Corp): There should be clear guidelines issued by HQ on that.

Aki: I'll repeat what Bob said. In the future, there will be rockets comparable to existing 5-m fairing vehicles because Dept. of Defense needs these. For SLS, who knows?

Nick Cowan: Does ground-based count for heritage argument?

Bob: If you only demonstrate stuff on ground, riskier than stuff demonstrated in space.

Aki: Repeating Bob for online audience, space-based heritage better; ground-based heritage is not nothing.

Dave Redding: Future heritage? E.g. Stuff that should be around in 2025?

Aki: Channeling Bob, that would be assessed as part of tech maturation plan. Aerospace will judge it for completeness and plausibility.

- Number of identified risks matter for color and cost. Bob, correct me if I'm wrong, but I gather that > 3 major items at < TRL 4 will get you red rating.

Bob: Not certain, but it points you in that direction.

2. Keith Warfield's Observations on Past Decadal Surveys talk
    - Decadals want balance across disciplines, activities, mission sizes. Decadals only prioritize missions that leave money for other parts of astrophysics. That don't eat the whole lunch.
    - Decadal surveys should identify acceptable descopes
    - All past missions prioritized thought to be < 3 billion at time they were identified.
    - Missions prioritized for start without de-scope always have 3 or fewer new technologies to develop.
    - Stahl telescope cost model; used by aerospace. Suggests 10-m telescope costs $4 billion just for the telescope.

3. Matt Mountain presentation "The future of space astrophysics is in your hands"
    - Myth 1: Large missions "eat the lunch" of smaller ones. They are always about 30% of total SMD budget.
    - Myth 2: LUVOIR will cost $20 billion when scale-up JWST. Telescope was about 17% of JWST. Big cost (half of cost) is always spacecraft and instruments. Real mission costs for warn LUVOIR are not intuitively scalable from JWST.
    - Myth 3. Here's where we get into a difference of opinion. Warfield says Decadal Surveys only choose missions < 3 billion. Matt believes that is a myth. Flagships are the foundation of decadal studies and only one cost < 3 billion in FY16.

Keith Warfield: Not a contradiction. He said *after* they got built only one of them cost < 3 billion.

- Matt also makes a cogent point that marginally capable experiments don't achieve the goal (e.g. Tevatron didn't find Higgs boson). Whereas Large Hadron Collider was designed to make meaningful null result and actually found the thing they were looking for. When we design conservatively so that if we don't see something we can learn from the null, that's when we detect the thing we want.
- Search for life is compelling for a lot of stakeholders.
- Ground based ELTs set bar high for transformative science in 2030s.

4. Lee Feinberg presentation on Lessons learned from JWST
    - On JWST, no single metric drove mission cost.
    - Someone makes a point that spacecraft + instruments are > 50%
    - Question: Mission ops. before phase E?
    - Lee: I have to check.
    - Aki: Slides for all of these presentations on LUVOIR public website.
    - Lee has said many times that cryogenic testing is expensive.
    - If can phase money properly over mission development, can save it.

Matt: Testing bleeds into which piece of pie?

Lee: Doing 50 K thing (can't hear).

Shawn: Cryogenic is expensive.

Unknown questioner: Does this include civil labor costs?

Aki: Yes, full cost not including international.

Brad: International includes launch services. It is not included.

Julie Crooke: HQ said launch costs will be advised for this study.

Discussion whether HQ actually said we should include launch costs.

Aki: For moment my understanding is that we are not including launch cost in this study.

- Lee's bottom line is aperture size contributes to all things but is not the biggest JWST cost driver. That was cryogenic.
- Question for clarification about whether you are charged for launch vehicles. Decadal will assume a number.

Aki: So in Decadal, we get charged a launch cost. So factor that in. We need official HQ guidance on launch and we want it sooner than later.

5. Slides from Alan Dressler on the Survey of Surveys report
    - Scheduling mix up for planned telecon, but he sent slides of what he intended to say.
    - "High profile missions" = performance-driven missions rather than cost-constrained.
    - Important for Decadals to strike balance between high profile missions and smaller completed ones.
    - Recommend that projects state which aspects of a project can be descoped and which are more essential.
    - Include descope and cancellation options. They made an example of the cancelled GEMS Explorer-class mission.
    - Quite possible future Decadals will take more hard-nosed attitude about controlling mission creep.

- What does this all mean? Not one clear message.
- Aki's general thoughts on all of this:
    - Don't defeat ourselves with low expectations. Don't prematurely descope ourselves.
    - Remain flexible to change.

Brad: Two architectures

Aki: Agreed, this is wise.

- Goal isn't to get in a particular cost box. It is to convince ourselves first and then whole community of mission being possible and worth it. It's the "worth it" that matters.
- Curious to see what take-homes you all got from this series of presentations.

Jason: I agree with last point (possible and worth it). Do we know what a 12-m LUVOIR would cost?

Aki: No.

Jacob Bean: Are we sure it'll be > 3 billion?

Brad and Aki (in unison): Yes.

Jacob: Almost seems that suggestion from Warfield is irrelevant. We are being asked to do something to something outside of that box. We can only ignore it.

Brad: My informal talks w/ Paul Hertz about how far out level of JWST expenditure goes. This is space we're talking about.

Shawn: Difference between 5, 10, 15 billion dollar mission might not be cost per year but number of years to build.

Aki: Grunsfeld and Matt Mountain have said that with extremely compelling science case, it is not impossible to bring in extra money.

Brad: Our job is to make it so attractive people don't care what it costs. I'm exaggerating for effect.

Lee: JWST money came from many places.

Aki: Now there's resentment and we're dealing with about that

John: To cost question, if it costs 10 billion, guarantee it gives 10 billion $ worth of science. HST has returned its cost 5 – 10 fold. Convince community that LUVOIR is worth whatever it costs. Our biggest enemy is ourselves. It's community coming back to Decadal Survey and thinking it'll eat everyone's lunch. Cost mission based on its value to discoveries and return. Make it worth 4-5x as much for the science.

Aki: When I say remain flexible, it's also about other things like new coronagraph designs. There was a big advance in last 6 months on coronagraphs that relaxed our stability requirements.

Nick Cowan: One reason HST was so revolutionary because kept it on going. Expected mission lifetime?

Aki: To be costed by Aerospace, we have to decide its prime mission lifetime. 5 years?

Brad: But they won't spend that much for 5 years.

Aki: From beginning, there was a strong desire that LUVOIR should last 25 years and have multi-generations of instruments and have serviceability. We have to design it to be serviceable but we don't have to decide how to service.

Avi Mandell: If a component has to last 25 years, that's a big risk.

Question about how HST design lifetime. 25 years for telescope + 5 years for instruments.

Brad: Yes, instrument lifetimes shorter.

A point about needing to convince community that LUVOIR is valuable. Funding wedge has a lot of pressure on it from other areas.

Late afternoon discussion on aperture size choices

Brad: Let's continue discussion on mission architectures. I will summarize what I have heard. I think I've heard a sniff of consensus that there's a sweet spot at 12-m aperture: great science, fits into 8.4 m fairing SLS, compatible w/ existing test facilities, mass is reasonable. We prefer on-axis design. The preferred telescope optical design is RC. Challenge with RC will fall squarely on HDI to decide if 3 by 3 field is big enough.

Aki: For today, most important thing is to pick aperture sizes. A lot of design details will flow our of instrument requirements. Don't need to specify now.

Leonidas Moustakis: Out of whole list, one item we don't have enough info on is on-axis. Fluidity between on- and off-axis based on instruments and coronagraph designs? We haven't discussed enough.

Aki: More discussion relevant to this tomorrow.

Brad: On-axis telescope really hard to package.

Matt Bolcar: Right now decision should be size of aperture. After that it's a fluid decision about on- or off-axis.

Shawn: Same thing true about optical design.

Brad: We want 2 mission architectures. If we look at another design, will we go up or down? Down gives wider variety of vehicles and simpler mission. If we go to 16-m, there are obvious science advantages. Then we'll definitely be out there in terms of risk. We will have to look at new test facility. There are trades we can make. We have been encouraged to go up but maybe we will decide down is more realistic.

Nick Cowan: Why do we have to start from 12-m and go up or down? Why not do 8 and 16 m? And understand reality is in between.

Aki: We can decide on that. I brought poker chips – we're doing the thing again.

Debra: Do we get I voted stickers? (laughter)

Dave Redding: Is going from 12-m to 16-m transformational? I've not seen thing that says it has to be 16-m

- If exoplanets eta_earth is 0.1, then we want 16-m.

Jane: We need to be realistic about JWST experience. Community will be angry if we don't get cost right first time. We need to be careful about not telling ourselves lies about what this will cost.

Daniela: From my perspective, 10-m or around it is a wash. The real transformation change happens above 16-m. Anything about IMF and star formation will be > 20 m.

Courtney: Since Scott is in room, what size of HabEx?

Scott: 4-m monolithic off axis; 6.5 m segmented off-axis. The latter is more TBD.

Lee: 12-m is nice sweet spot. From my point-of-view, I want to choose one architecture and go deep with it.

Bekki: I don't know which size is sufficient without knowing lifetime of mission.

Brad: This will come up in design reference mission. Do we have enough mission lifetime?

Aki: For exoEarth science case, it takes 2 years of 5 year mission. Assume and adopt that we will refurbish and upgrade this telescope facility over decades.

Kevin: Two years is 30 Earth like planets for a 12-meter.

Nick: I think LUVOIR is being sold to community and public based on habitable planets and biosignatures. People are conflating exoplanet science that scales nicely with different sizes with doing biosignatures, which requires a huge aperture. To characterize and look for biosignatures, it has to be really big. 16-m is where you start to be able to map Earth.

Aki: For me, it's not about how many Earths we find. It's about quality of data on these planets. Want to be definitive about biosignatures.

Julie: When we sat down with Aerospace, and we asked whether to study one or two architectures, they said two.

Bob Bitten (Aerospace): We need to look at science tradeoffs with cost for different apertures.

Marc P: Lee's strategy makes sense. We don't want to leave it to Decadal to fill in missing things if we hand them two half-baked designs rather than a complete one

Julie: By doing 2 architectures, we can still study all instruments, just not all at the same time.

Walter Harris: We had same discussions with HDST, we looked at aperture size. Question was if I had to go to congress and say that we can find a habitable Earth with this aperture, that's precision we need. 30 planets was the bare minimum. This has a bigger science case, but we have to design it around what's the compelling science case.

Marc: 8-m vs 16-m is two completely different science cases.

Shawn: I think that might be ok. We don't know what rockets will be around when it launches and we don't know budgets and we don't know Decadal Survey will treat words like "programmatic balance." Scalability of this concept is one of our key strengths. Helps us be responsive to different rocket fairings, budget realities, etc.

Chris: Idea of scalable design and one design is smart. We need to make aperture decisions on exoplanet yield. We may want to consider design that we can update if more info comes along. If eta earth 5x higher, make instruments we can degrade?

Aki: Lee, I understand there's a natural impulse to study things in more detail. But there's zero evidence from previous Decadals that this actually helps you get a mission past the Decadal. Given advice of Survey of Surveys report, important for us to demonstrate how our science scales with aperture not let the Decadal do it. Decadal will define descopes for us if we don't do it. We should study the descope.

Lee: We can do that without two detailed designs right?

Aki: But we don't know what instruments fit into two different sizes.

Dave Redding: We need to go into detail to show we're technologically ready (TRL)

Daniela: I support Aki's point. If we don't do scalability problem, we don't want them telling us how to descope science. We want to be the ones who tell them.

Julie: We have enough resources to do two studies.

Aki: We don't have enough money to do a LOT better job on just one architecture anyway.

Lee: I'm not totally against two architectures. There is a step function between fairing sizes. How many instruments can you fit, what FOV is a packaging study. Depth I was talking about is going into e.g. 65 nm mirrors, here's a production plan. Show what schedule in cost is and production details.

Julie: What's stopping you from doing that?

Lee: I think we can do both.

Shawn: Let's pick two and have a primary focus one.

Matt: To build on that, it's beneficial to explain in more detail what we mean when we say "study the design". We will run two architectures through GSFC Integrated Design Center. The IDC won't address things like picometer stability. IDC will do detailed dive on 1st mission architecture. If we do that for larger design, there's an easy story to tell. If we do a deep dive on smaller one, not as useful. We will do deep dive on the bigger one. Going down from there is descope option.

Brad: Downscope should be from 16-m to 12-m.

Julie: But we need to show something that fits in 5-m fairing or we're dead.

Aki: We need to show best to worst descope. For larger architecture, let's ask for what we actually want and study it. For option B, pick something that fits into a launch vehicle that actually exists.

Jane: What's largest aperture we can fit into the fairing?

Nick: Peril of having 16-m and 12-m or 8-m descope is that science can be very different.

Vikki: We'll cut our sample by a factor of 3 on characterization.

Jane: (slide pulled up) Biggest thing you can put into 5-m fairing comfortably is at least 9, maybe 12.

Aki: If put 12-m into 5-m fairing, need to sacrifice instruments.

Vikki: What about 10-m?

Lee: Given current instrument suite, more difficult.

Brad: If launch vehicle not available, we go to 9.2-m. But maybe we can't do mission at 9.2-m.

Matt: Science case changes.

Lee: Or technology changes.

Scott Gaudi: Tech different with different architectures. I encourage LUVOIR to do something similar to what HabEx is doing. Do it so you cross some breakpoint so tech is different.

Someone: Thing has to be flexible enough to do science cases we don't know about yet but will know in 20 years. Do we want to throw a lot of weight behind a telescope we're only kind of excited about now? Consider a 9-m and a 16-m. Science from a 9-m is fundamentally different. This pushes me into bifurcating 9-m to 16-m. 12-m may be what we want in the end but maybe 16-m is what we need to study in the next years. We are considering the 16-m because it's going to give us flexibility to be a 50-year-old telescope doing revolutionary science.

Brad: Let me remind you of another of Paul's points. If you want a 12-m, I want to know the delta to go to 16-m.

Karl: I'm worried about 9.2-m to 16-m for exoplanet science case. We've emphasized statistical science case. By 2020, we may not have better constraints on eta Earth.

Aki: A lot already done on 12-m, which was HDST. I prefer to look on either side of that.

Mark Marley: NIR characterization much better at 16-m.

Brad: That is our killer app. That makes everyone sit up and pay attention.

Aki: For bigger architecture,we should ask for what we want.

Karl: Detailed design for 12-m in HDST report.

Aki: But if HDST is in between two things we study, I feel ok about that.

Debra: We were told to look at more challenging architecture. I don't think Paul will object to see descope from 16-m to 12-m.

Dave Redding: Let engineering team tell us what the size fits into fairing?

Aki: Let's be kind to them and say that any number we put down is plus or minus a little bit. Should we vote now?

Courtney: I think we're saying we want biggest telescope that will fit into fairing. So 9-m with three instruments or 12-m with two instruments?

Karl: ATLAST study did look into this.

Aki: But no instruments. Just telescope.

Karl: What is level of fidelity of previous work?

Aki: Good on telescope but almost nothing on instruments.

Marc: No serious work on any telescope bigger than 9-m.

Lee: We did a couple packaging studies on 12-m.

Julie: Of the telescope alone without instruments.

Aki: Point of 9-m is we don't put it into SLS. Fits into 5-m fairing.

Discussion about on- vs off-axis. We don't know yet. We don't need to decide yet.

Vikki: Yield calculation for 30 Earths in HZ for which mirror diameter?

Chris: About 11-m. Characterization time for 12-m peaks at around a week.

Aki: I like your philosophy, Chris, from counting statistics point of view. But lots of people in exoplanet community think this is overkill (number of Earths).

Vikki: This is a limit on how long you have to integrate on targets.

Aki: You can co-add. People don't do an entire transit spectrum in one go.

Shawn: Co-adding two or three not a huge problem.

Vikki: Going down to 9-m, what are the numbers?

Chris: Vikki is asking if we go to 9.2, when you stick that histogram up, where does peak of integration time occur? Tack overheads on when planet moves…

Aki: This is ok. You come back to the target. Don't observe continuously for a month.

Nick: It can disappear inside IWA.

Mark M: These values (on Chris slide) for optical observations. For NIR, much longer integrations.

Scott: How many is enough to justify cost of mission? We can characterize some number (on HabEx). You can assign whatever probability you want that there will be habitable worlds. For us it's a few, for you statistical sample.

Nick: HabEx still doing starshade? Better for characterizing.

Aki: Not much better. Higher throughput of starshade still must deal with 4-m aperture.

Scott: Does let us go to longer wavelengths.

Brad: Starshade is a future add-on for LUVOIR. One might say phased way of doing it is wise.

Jacob: Can we see later slides? In 100 hours what sort of spectrum do you get?

Discussion on integration times.

Shawn: For the record, I don't want to be in charge of the communications team if we have a three-year observation of a possible biosignature.

Britney: For survey capabilities, change in survey size and resolution for larger telescope is highly motivating for planetary science. You can start to do flyby-class (km scale res or maybe better) or better missions. 2-5 km resolution would be "awesome." This could replace flyby missions. We can do this at 12-m. But 16-m would enable 1 km objects in Kupier belt. This is a huge deal. This is incredibly enabling for planetary science if done correctly. E.g. Huge for ice giants. Temperature issue: You lose a lot of Solar System people stopping short of 3 microns. You lose most of science you can do with spacecraft vs. ground based.

Aki: In addition to being expensive to test cold, going much below freezing poses serious risk to UV sensitivity.

Britney: Beyond 3 um is a killer app.

Matt: Table temperature discussion. Not what's being decided now.

Britney: I wanted to at least talk about killer apps. Gives you leverage outside of astrophysics community.

Marc: Even if it's warm, nothing prevents us from putting 3 um detector.

Geronimo: Competition with ground-based telescopes with warm LUVOIR.

Marc: We struggle with compelling astrophysics science case with anything below 8-m.

Choices to vote on: 16-m, 12-m, ~ 9-m

1st round of voting for Aperture A:

9-m: 0 chips
12-m: 5 chips
16-m: 16 chips

2nd round of voting for Aperture B:

9-m: 16 chips
12-m: 5 chips

Communications and Outreach (Debra Fischer & Shawn Domagal-Goldman)

- Go into Google Drive, look at colloquium talk outline, make recommended changes with track changes and comments.

- Contribute slides you have for slide deck.
- Lastly we need a new name.

Aki: Are we sure?

Shawn: There have been calls for a new name. LUVOIR is not brand-y enough. Let's have these conversations informally.

Brad: Telescopy McTelescope is out (laughter).

Courtney: I want to echo my earlier request for a new name for O/NIRS as well. John has suggested ELVIS.

Kevin: Newly branded Origins Space Telescope team doing panel discussions. Emulate that?

Shawn: We could do that. We have a spreadsheet in Google Drive that has where STDT members have given talks.

Aki: I'm mystified how OST is affording these panel talks.

Shawn: What if we do them around the time of interim report?

Ravi: Stefan online comment. FIRS has poster papers for AAS.

Aki: LUVOIR will too. Also, we have splinter meeting for hands-on work with simulation tools.

Shawn: Meetings we should have a presence at?

Courtney: Can we have stickers/buttons "Ask me about LUVOIR"?

Shawn: Good idea.

Brad: Last item for discussion is prep for meeting tomorrow. Start with short presentation from me and I'll talk about the architectures we've decided to study. Then Debra will do science cases and Aki the instruments. Anything else to discuss?

Aki: Julie will say something about study plan tomorrow.

Julie: That'll be really quick.

Scott: Fill whole time with slides or leave some time for discussion? Agreement to leave time for questions and discussion.

Debra: We need same metrics so comparison is useful.

Scott: We'll compare notes in breakout sessions. Aki and I will lead discussion at end about language and metrics.

David Redding: This is how we're planning to do tech session. Please come if you want to discuss tech.

Scott: We need to identify areas of complementarity to save resources.

Aki: As a general principle, in everyone's best interest to go into Decadal without contradicting each other on anything. Makes us both look bad if we aren't consistent with each other.

Day 2 (Thursday Nov 10, 2016) – LUVOIR & HabEx teams

HabEx Science Cases (Scott Gaudi & Sara Seager)

- Highest level goals: Detect and characterize handful of ExoEarths; characterize nearest planetary systems. Given this, maximize general astrophysics science potential without sacrificing primary exoplanet science goals.
- Science goals "very exploration based"
- Explore nearby systems "as systematically as possible".
- A lot of subtlety involved in words "detect" and "characterize." They want to search for signs of habitability and biosignatures.
- Mission optimized for exoplanet imaging.
- Their goal is "a survey kind of aspect" to study nearby systems in great detail
- Emphasis on Keith Warfield's slide showing all past prioritized decadal survey missions thought to be under $3B.
- Only allowing themselves "three tooth fairies" (three new technologies).
- They do not view HabEx as an exoplanet-only mission.
- They want to focus on 400-1000 nm for exoplanet observations.
    - They are considering stretching to longer and shorter wavelengths.
- Considering 1-2 band UV channel in exoplanet instrument (they're hoping to see signatures of ozone cutoff).
- They're considering architectures w/ coronagraph and/or starshade (or multiple starshades).
- Not looking for a large statistical sample of Earths.
- UV for > 2.5 m a "novel capability"
    - Focus on UV for general astrophysics instruments.
- Discussion of parallel observations (UV).

Sara: We can explore each nearby sun-like star down to the noise floor including M stars

HabEx Architecture and Instruments (Keith Warfield)

- STDT selected 4-m unobscured and 6.5-m telescope designs for study
    - Discusses how they landed on these sizes based on heritage.
- L2 assumed as the orbit.
- 5 architecture variants being considered right now for 4-m design. They will repeat this for 6.5-m design.
- Surprise for 4-m aperture: Al mirrors helps with coronagraph contrast (rather than silver). Slight hit on throughput, but it improves overall coronagraph performance.
- Favored mirror material is Zerodur; has low coefficient of thermal expansion (CTE). Evaluating ultra low expansion glass (ULE) right now.
- Starshade to fit into 5-m fairing.
- Vector Vortex Charge 6 coronagraph "pretty exciting news for us"
    - Contrast < 10^{-10} from IWA outwards (2.4 lambda/D)
- 100 – 350 nm UV spectrograph
- Want to see if they can leverage GSFC microshutter work.

Question about on- vs off-axis: They're still considering.

Daniela: When you have only a few objects, there's a probability you'll detect zero. Is this still interesting?

Scott: Our primary science goal is deep dive on N number of nearby systems. If possible, if we can fit in constraints, expectation number should be prob. of getting zero should be quite low.

Sara: It's called HabEx so we're supposed to find something habitable.

Scott: Given level of uncertainty in these assumptions, hard to say with 99% confidence

Sara: Now with Proxima Cen b discovery, we're going to hammer away as deep as possible on nearby stars. We have confidence that small planets are common. It's doubtful we'll come up with zero. We might have zero with water and oxygen. Eventually with LUVOIR and other things, we do surveys.

Shawn: But LUVOIR can hammer these systems very deeply too. Don't cast as one mission does one thing and one as another

Sara: Reason we're here is we want to present menu of options. If we could, most would choose the biggest thing, but don't think this will happen.

Scott: Don't know what range of future constraints will be. Want to provide broad ensemble of options. HabEx not great leap forward; first step forward. LUVOIR is "going for broke." Can we/do we want to do this as one or two step process?

Kevin France: Extending wavelength range down to 100 nm; what mirror coating to use? On primary optics and internal optics of instruments?

Keith: Gary can give coating tomorrow.

Scott: Going with magnesium fluoride?

Keith: Going with HST coating (mag fluoride). Goes to 120 nm. For UV spectrograph only – it's only thing requiring that now. If adopted as gen. astrophysics payload, then we have to absorb the lien and coat with different material.

Scott: That would invoke one tooth fairy.

Leonidas: Does f-ratio choice affect performance of starshade?

Keith: I don't think so.

Stuart Shaklan (online): Doesn't matter.

Scott: I think what would be useful during the breakout session today to hear input from LUVOIR section on which science gen. astrophysics drivers are most compelling such that if we descope to one general astro instrument, which should it be?

LUVOIR Mission Philosophy (Brad Peterson)

- Instructions given to "think big".
- Grounded in reality of launch vehicles available. Going to assume SLS available at time to fly for high end. 16-m telescope at high end to deploy on orbit. Should SLS not be available, next biggest thing we can fly in 5-m fairing on Delta 4 heavy (~ 9-m aperture).
- Looking at science cases, they changed markedly in 10 – 12 m range. Very different missions depending on how big we go. 12-m is probably "sweet spot" for number of reasons, and can make use of existing test facilities.
- L2 orbit and serviceable. Nominally 4 – 5 instrument bays. Not clear all filled on launch.
- Scalable and upgradable.
- Longer term secondary missions such as later starshades under consideration.
- As with HabEx, killer app is exoplanet characterizations. But driven by general capabilities for broad astrophysics including COR, solar system, exoplanets.
- Want to provide most capable missions we can with currently conceivable envelopes.

LUVOIR Science Cases (Debra Fischer)

- HabEx and LUVOIR are one team divided in half. All people on both sides of artificial divide right now will end up on ultimate mission.

- Looking for habitable planets & biosignatures and have broad range of astrophysics and solar system science.
- Goal: Statistical study of habitable exoplanets. Have factors of 100 increases in general astrophysics capabilities.
- Exploring 8 – 16 m architectures.
- Want to enable decades of science, and be able to answer and generate not yet conceived questions.
- Need > 8-m to see individual solar-type stars in giant elliptical galaxies.
- For most of Earth's inhabited lifetime, its atmosphere completely different with lower oxygen.
- Access to multiple bands of molecules to build up signal and confidence.
- Observing HZ planets in NIR "really does demand large telescope aperture".
- "Amazing bounty" of exoplanet types (the exoplanet zoo) comes along with characterizing Earths.

LUVOIR Instrument Suite (Aki Roberge)

- At 2nd STDT, put together candidate instrument suite list on basis of science observation needs.
- Top priority instruments:
  - Optical / NIR Coronagraph (contrast 10^{-10} or better)
    - Leaning towards R = 150
    - Baseline 0.4 – 1.8 um but really want 0.2 – 2.4 um
  - LUMOS (UV instrument)
    - FUV – NUV; high res point source spectroscopy (R ~ 10^5)
    - Med. Res. Multi-object spectroscopy w/ microshutter array
    - NUV imaging
    - Described as "major upgrade of HST STIS"
    - French Space Agency to design second complimentary UV instrument w/ spectropolarimetry.
  - High Definition Imager
    - 4 – 6" FOV
    - Optical – NIR bandpass
    - Considering sub-microarcsec astrometry to measure planet masses and do other things
  - Optical / NIR Spectrograph
    - Multiple spectral resolutions
    - Possibly able to do high-precision radial velocity to measure planet masses
    - Possibly template matching technique
    - High photometric precision for transits
    - Probably the least completely designed instrument right now
- LUVOIR simulations tools
  - Online at http://www.jt-astro.science/luvoir.html

Question about wide-field imager also having spectroscopy mode? Answer is that they're thinking about a grism.

LUVOIR Study Plan and Schedule (Julie Crooke)

- 9-m and 16-m designs to be studied
- Several working groups established
- Plan to study Architecture B while writing up Architecture A

Solar System Science with LUVOIR and HabEx (Britney Schmidt)

- Survey & characterization
- Pathfinder measurements (future target reconnaissance)
- Orbiter-type science on targets that will never been flown to
- Challenges:
    - Visible detection dominated by reflected solar light
- Highlights:
    - 10 – 100x HST area
    - < 0.01" res
    - UVOIR wavelength coverage (100-3000 nm)
        - Emphasis on NIR
    - Wide field imaging (> 4 Gigapixel)
    - Broadband spectra
    - Solar exclusion angle (< 45 degrees; Venus)
- Key program: Ice giant aurorae/airglow
    - We have no spacecraft going to Uranus and Neptune
    - How aware of LUVOIR is OPAG?
- Key program: Satellites of giant planets
    - Enable detection of satellite surfaces and emissions from aurorae and emissions (Ganymede aurora, Io volcanism, Europa plumes and aurora)
- Key program: Small body interiors
    - Also surface characterization
    - LUVOIR could act like a spacecraft mission to small bodies
    - Test whether object in hydrostatic equilibrium by looking at crater relaxation
- Key program: Remote comet activity
- Key program: Centaurs and KBOs
    - We know little about these objects
    - "Pluto and friends"
    - Can see 1 km objects at 50 AU in short exposures
- Key program: KBO-Oort Cloud
    - Resolve surfaces of KBO dwarf planets
    - Resolve Planet 9
- Key program: Atmospheric dynamics
    - Venus, Jupiter, Saturn, etc.
- Key program: Science beyond 2 microns

- Absorptions of organics; important for Kuiper belt
- Absence of diagnostic features < 2 um for asteroids

Aki: Why does Ganymede have a magnetic field but Mars doesn't?

Britney: Good question!

Geronimo: One is rocky and one has a liquid interior.

Britney: Ganymede has high-pressure phases of ice -> relevant to exoplanets with same bulk compositions (super-Earth water worlds). Why Ganymede has an internal magnetic field is still open question. Ganymede has internally driven magnetic field. Other moons have induced mag fields. But Ganymede has induced and internal mag field.

Scott: Internal heat from tidal dissipation not enough to dive dynamo?

Britney: A source of internal heat but not enough for mag field.

Aki: It is very important for exoplanet stuff. One critical question about whether planets can or cannot be habitable is whether or not they have magnetic fields.

Walt: We don't understand why. It's a longer day than Europa. This is a general thing we're now realizing from New Horizons that there's a subsurface ocean on Pluto. Planetary scientists didn't anticipate that. Subsurface oceans probably common throughout solar system.

Britney: Methane not just easily condensed and also generated by differentiation. Distribution of methane can potentially tell how active interiors are.

Shawn: Bertrand Mennesson has question online. What can Webb do in NIR?

Britney: It's a huge difference. We can detect there's stuff there with Webb but can't spatially resolve it. Huge collecting area matters. Detecting existence is one thing. Resolved spectroscopy is quite another thing. Anywhere you can resolve multiple features on planet will allow rotational characterization. Seeing where it's at on the planet important.

Aki: O/NIRS still will be capable out to 5 um. Useful on bright objects not dominated by telescope background. I don't know what size objects are bright enough.

Geronimo: What we'll try to do today is bring temperature onto the table. You can do bright stuff but KBOs and small bodies you can't do.

Aki: Pallas and Ceres?

Britney: Maybe but not be able to resolve differences. Then JWST is our best bet. We don't have to go farther into NIR. There's important stuff at 3 and 3.4 um. Important thing is for small transitional objects with salts and dirt on the surfaces. Centaurs, comets don't have water ice bands because of surface deposits.

Aki: Lee care to say a few words about the temperature trade?

Lee: Read the white paper. 260 K is OK before you impact UV. After that things get tough. Might be useful to compare Webb to LUVOIR. Good to see what LUVOIR or HabEx could do versus Webb so we can see what wavelengths etc.

Britney: Serious game changer for Solar System if you can go out to NIR. It's a trade space to think about but potentially gets you a lot in terms of buy-in.

Aki: As I understand the technical trade, it really poses a great risk to UV. We have to choose.

Lee: Or huge cost. Not technically unfeasible but you could double cost of observatory.

Britney: Might or might not. We haven't talked about it. I'm not trying to lose the UV. But we're pushing back on assumption that we kill UV by trying to go colder. I realize there's a cost element but there are 10s of missions to Solar System objects this mission could replace.

Lee: Just out of fairness, UV was one of 10 issues in the telescope temp trade. Lots of other technical details.

Dave Redding: If we have a nominally warm telescope that we could cool on occasion, could we go below these transition points without permanent damage?

Lee: That's incredibly complex. We're trying to achieve picometer stability that's in some regards as difficult as LISA. If coronagraph community pulls a miracle and relaxes stability by two orders of magnitude, this becomes more manageable.

Dave: What if we don't run coronagraph cold?

Aki: I think we assume O/NIRS is cold even if telescope isn't.

Dave: What if we give up wavefront error?

Aki: Do we still get exoplanets? These decisions are coupled to COS UV science, coronagraph – we have to think about all of it.

Nick: Ever precedent for solar system giving money to an astrophysics mission?

Walt: We talked at DPS. One way to advance the case is to get Solar System community to put this into their Decadal. If they do that, that's something we can have a discussion about. Anything prioritized in Decadal is an option for New Frontiers mission class. No precedent but not impossible. We want to make sure we don't leave wavelength range on table when we can do it without doubling cost of observatory. Getting closer to 2.5 um helpful.

Lee: 260 K is the point where lots of molecules start sticking. Still has challenges. Exoplanet community has same desire to go to longer wavelengths.

Shawn: Possible to give Decadal proposal to make decision rules. If either mission prioritized coming out of Astro Decadal, could go to Planetary Decadal and ask what changes to this would enable more planetary science? See if planetary community wants to prioritize changes.

Geronimo: What happens for non-coronagraphic obs. that are cooled? Do you really have to recalibrate whole instrument?

Lee: We have to study how long it takes to cool down, what are gradients?

Coronagraphy with segmented apertures (Dimitri Mawet and others)

- HabEx narrowing in on potential coronagraph architecture
  - Charge 6 Vector Vortex w/ off-axis 4m monolith
  - IFS w/ R~70
  - Imager + (fiber fed?) spectrograph
    - R ~ 1000 spectrograph for characterization

Laurent Pueyo

- LUVOIR hasn't narrowed down design yet. Want to narrow down telescope architecture before coronagraph
- If target farther away than 4.4 pc, stellar angular size no impact on contrast
- Promising initial results with Charge 6 Vortex

Garreth Ruane

- Vortex coronagraph gives high throughput at small angular separations, even with segmented telescopes
- Charge 6 can give star suppression better than 10^{-11}, insensitive to low-order wave front errors. Need only < 9 – 2 nm of defocus, astigmatism, coma, …
  - Nanometer telescope stability requirements!
- Off-axis performs better. Their goal is to improve designs for on-axis telescopes
- Deformable mirrors can increase throughput

Ji Wang

- Modeling of combining coronagraphy with high-dispersion spectroscopy and spectral template cross-correlation.

- Cross correlation function = data product. Increased sensitivity for molecule detection
- Can measure spin of planet and do Doppler imaging
- High dispersion coronagraphy (HDC) -> characterize Prox Cen b from ground
- HDC can enable:
  - Planet detection and confirmation at more moderate starlight suppression
  - Detecting molecular species
  - Measuring planet rotation
  - Measuring surfaces and atmospheres
- Relax star suppression requirement by 1-2 orders of magnitude. May be needed for CO_2 detection (on modern Earth)
  - Wang et al. 2016
  - Speckle chromatic noise. Can mimic absorption lines of planets.
    - Width of speckle "lines" mimics oxygen A band
    - Introduces hit at lower dispersion regime
- Makes point that although HabEx is smaller, it's exoplanet focused so can dedicate more time to a given planet
- "Sweet spot for HabEx" is R = 400 and star suppression 5e-9 (but still can't detect CO_2)
- "Sweet spot for LUVOIR" is R = 1000 and star suppression 5e-8 (ditto re. CO_2)
- Detector noise major factor that limits performance of space based HDC instrument
- Speckle chromatic noise impacts performance at low spectral resolution. Recommend R > 1000 to remove this effect.

Sara: I love this idea in principle. Proposing to use for detection or enhance characterization?

Ji: Follow-up and characterization.

Sara: I want to emphasize that you don't know what molecules the planet will have. I heard it was for detection and not characterization. Fine from ground but from space we don't want to rely on this. We don't want to have to know what molecules it has and have to rely on post-processing from space.

Jacob: Great talk and exciting. Post-processing assumes you lose continuum. Can you measure abundances?

Ji: Yes.

Jacob: Important to emphasize you can't measure continuum so can't get direct abundances, only relative ones.

Mark: To me, this would be follow-up for measuring things hard to see otherwise. Want to stress lack of absolute abundances. Need classical reflection for continuum. We can't be sure of what species there will be. Wouldn't want to rely on this for first order detections.

Ji: But after planet detection you can try variety of combinations of spectra to see which gives you best match.

Mark: Have you changed pressure broadening? What if template is off based on pressure? How badly does that impact?

Ji: We've done calculations for ground-based obs. We tried mismatched template and that reduces detection significance by factor of 10, which is huge.

Jacob: But it's not sensitive to pressure.

Mark: But if line widths are wrong cross-correlation significance reduced.

Ji: We used two mismatched spectra. These two spectra generated independently and used as case study for how much signal reduced. From that experiment, SNR reduced by factor of 10.

Shawn: Even if you can't measure, can predict based on which line strengths appear and disappear?

Jacob: For orders of magnitude changes in abundance?

Shawn: For methane as a biogisnature, it would be useful to get order of mag abundance. For exoplanet science, we want to push for methane. This could help warm telescope to get methane.

Ji: Looked at methane from ground but excluded thermal noise.

Kerri Cahoy (online): Couple logistical questions. These spectra aren't hitting detector in same way at same pixels and same time. Calibration issues, offsets? How robust to that? And how unique? When doing cross-correlation, there are degeneracies.

Ji: Peak in cross-correlation only necessary condition for detection. Rely on RV to confirm planet.

Kerry: (missed most of this – about cross correlation on speckles)

Ji: You would get a peak. This is already considered. Speckle noise mimics absorption bands. Filter will remove majority or all of signal from speckle noise. You apply high pass filter and remove all low frequency component. Speckle noise will only be at certain spectral frequency. Only mimics absorption bands at R ~ 100. Interlopers are lower frequency so remove with high pass filter.

Laurent: You find optimum is at medium res. If you don't go to R = 10000 – 100000, can't do Doppler imaging. Limited by detector tech, nothing else. Looking at this slide, have you looked into occulter? Relax occulter requirements?

Ji: We haven't looked into that.

Scott: If you don't know what species are there, if you cross correlate with enough templates, you'll get detection whether something is there or not.

UV Coatings, Polarization, Coronagraphy (Matt Bolcar)

- Sensitivity in UV requires aluminum primary and secondary mirrors
- Al oxidizes very quickly and that suppresses UV
    - Need coating to stop oxidation. Maintain reflectivity to as short at 110 nm

Kevin France: Question about temperature of UV coating process. They want to cool the process down. Incompatability between coatings and diffraction gratings.

Brad: Talked about deposition of Al in space. Problem of telescope outgassing. Problem of getting a uniform coating.

Lee: Difficult to do. Huge problem (lost track of this technical conversation).

Karl: Any data on how uniformly these coatings can be deposited? (speckles)

Matt: Thing looked at is repeatability.

Dave: Coating stresses?

Matt: We have to make a good stiff mirror, I guess. I don't know how mirror deformation will affect things.

Debra: Timeline for figuring out if Al+Fl3 coatings will work? These give better UV sensitivity < 100 nm.

Matt: Looking at this with internal GSFC funding.

Kevin: Also active APRA project between JPL and Colorado

Debra: After you have coating, is it a matter of time to see how long it lasts?

Kevin: We have environmental testing apparatus to see how coating age over at least two years in air, vacuum, dry N. Baseline is at least two years.

- Coatings can affect polarization. Can result in four incoherent electromagnetic fields that must be corrected by coronagraph.
    - If do nothing, coronagraph senses average of these four fields
    - One trick you can pull is to put a polarizer in front to separate two orthogonal polarizations, then correct each separately. But you lose 50% of light at the detector (or have to double your coronagraph).

Kevin: Sense of relative polarization ratios to not be an issue?

Matt: I don't know that. Studies we're going into will try to answer that question.

Some discussion about coronagraph channels covering slightly different bandpasses.

Matt: What is optimal number of coronagraph channels? (TBD)

- Al + Ag gives lower wavefront error at blue and red end
- Contrast in 400 – 490 nu band: Al does better than Al+Ag
- In red band (720 – 880 nm), they are comparable
- LUVOIR polarization study initiated for 9-m, 12-m, 16-m on-axis and 9-m off-axis
- To do:
    - LUVOIR needs to complete analysis of designs
    - Both studies need to improve fidelity of coating models
    - Optimize coatings to balance/minimize polarization aberration
    - Need to understand impact of cross-polarization leakage

Kevin: How are you determining polarization in simulations?

Matt: If you know n and k, that determines polarization

Kevin: n and k have to have some empirical data and they have error bars. If you fold error bars through analysis, are errors significant at 1e-10?

Matt: You could take data and add 3-sigma error bars.

Kevin: May be a tech demo that's not hard to do.

Dave Redding: Question about coating uniformity, thickness. Best to show good tolerance.

Aki: Why did they think in TPF-C days that all-silver mirrors were the way to go?

Karl: General astrophysics was brought in really late.

Lee: Drawback to Al. Over visible range, its reflectivity lower than Ag. Its throughput is 15% lower in visible.

Matt: Only put Al on mirrors for UV.

Karl: Al has less chromatic effect. More problems with Ag.

Exoplanet Characterization Breakout (only have detailed notes on the breakout session that Giada was in)

Planet Diversity (Leslie Rogers)

- Will naturally find lots of planets by optimizing for Earths
- How do properties of HZ planets correlate with system architectures?
- Planet properties within a given system may be correlated
- Range of secondary atmospheres? Which planets are geologically active? Which have surface liquid water?

Nick Cowan: Constraining magnetic fields? Potentially very challenging and pushes to different wavelengths.

Geronimo: Traceability matrix for how to address questions?

Leslie: Not yet done that. There is a ExoPAG Study Analysis Group writing a whole report on these topics.

Mark Marley: Retrievals for WFIRST. Looking at Jupiters. If you don't know radius, how well can you constrain it? Looking at multiple phases helps a lot with radius. Use scattering curve.

Jacob: What about patchy clouds?

Mark: Larger phase angles get more scattering from higher up in atmosphere.

Vikki: We have to report out work going forward.

Jacob and Mark: We really need retrievals.

Jacob: Need end-to-end retrieval experiment.

Shawn: Ravi and I have been trying to think about other types of planets besides HZ planets. Mark, I like your thoughts on this and Leslie for other parameters. Based on things we observe today (orbits, sizes), what can we do to leverage that? We have populations in these two axes. How to get yields? How do these control 1st level observables? Classic 3 bins of planets: rocky, gassy, in between. Farther from star, should be condensates.

Nick: I like condensate test.

Shawn: We can break into three bins Rock dominated, gas dominated, not dominated.

Nick: I think you can do mass bins. I don't think you can get radius.

Shawn: But radius is best data you have now. Looking back at habitable zone, Kevin Zahnle and Abe defined as region of water condensation at inner HZ and CO2 condensation at outer HZ.

Avi: For mission design, you don't just want to say breakpoints. Want to quantify how much you differentiate. Retrieval really matters.

Mark: We're doing this all for WFIRST. When you actually do it, your expectations shrink. Order of magnitude abundances …

Vikki: Are masses important to us?

Everyone: Yes!

Vikki: HabEx not capable of doing masses?

Shawn: Masses are important but let's not prescribe how to get them

Vikki: LUVOIR might try to do it with on-board radial velocity and astrometry.

Shawn: HabEx trying both but less capable.

Habitability (Nick Cowan)

- Defined by liquid water on surface of planet
- Partial cloud cover
- Land
- "Water is shiny"
    - Glint!
    - Polarimetric glint
    - Need small IWA
- Water is dark blue
    - Photometric mapping
    - Need large aperture
    - Need wide bandpass

Vikki: Need simultaneous wavelength coverage?

Nick: Ty and I are looking at this. It doesn't matter too much.

- Patchy clouds
  - Wide bandpass
  - Spectroscopic mapping
  - Need large aperture
- Water vapor, “surface”, pressure, albedo
- Atmospheric thickness
  - Rock spectral features
  - Need large aperture
  - Need wide bandpass

Vikki: Exposed rock important for biosignature interpretation. Continent detection crucial.

Discussion of treating planets as statistical population (as astronomers do) versus deeply understanding individual planets (as planetary scientists do).

Giada: Habitability false positives?

Nick: We looked into that in paper.

Giada: We should look into more.

Biosignatures (Vikki Meadows)

- To understand a biosignature, life is a planetary process
- Characterize host star, characterize planet, other planets in system
- Understanding context of what you’re looking at is really important
- Presence or absence of key molecules, models of photochemistry
- System science perspective
- We’ll come down to a probability for a given planet in the end

Nick: Glint and rotational un-mixing different from standard thing HabEx and LUVOIR want to do which is just integrating to get a spectrum.

Avi: Observational flowchart?

General agreement that’s a good idea.

Aki: The flowchart is a filter (pyramid). Lots of coarse observations of many targets, fewer and fewer more detailed observations of best candidates.

Jacob: I want to encourage looking at diversity of planets.

(Discussion highlights difference in philosophy between planetary scientists and astronomers. Astronomers want to take statistical approach to targets. Planetary scientists want to understand individual worlds.)

Queries from Exoplanet Yield Breakout to Characterization Breakout (Chris Stark)

- Discussion about do we include Mars-size planets in “habitable planets”?
- Eta_Earth for tiny Mars is 60%?
- Zahnle and Catling cosmic shortline is best work until today on smallest planets holding atmospheres
- Leslie idea about looking smallward of cosmic shortline with LUVOIR/HabEx to test the theory
- What’s our definition of a potentially habitable planet?
- Need to agree upon albedos and wavelengths for yields across HabEx and LUVOIR

How do HabEx and LUVOIR Work Together in the Future? (Scott Gaudi & Aki Roberge)

- If HabEx extrapolates up and LUVOIR down, we need to actually meet in the middle and agree. St. Louis Arch analogy
- “HabEx and LUVOIR skipping into the Decadal hand-in-hand, singing kumbaya”
- Don’t contradict each other on anything
- Don’t make decadal survey do interpolation for us
- Do not give appearance of competition or conflict
- If we go fighting or contradicting into Decadal, we both lose
- Gap between 9-m and 6.5-m. But we are resource-limited for interpolation study
- Suggestion:
    - At the very least: no contradictions, reconcile science, costs, risks. Common appendix for both reports?
    - Further options: Delta up from 6.5-m? Delta down from 9-m? Joint architecture that’s another ring of mirrors around the 6.5-m? Will require resources we don’t have
    - “Light touch” joint study? May be additional funding available for this

Aki: Won’t need to split the difference between 6.5-m and 9-m because 6.5 is JWST and 9 is JWST with another ring

Daniela: One difference is number of instruments. What do you lose for science capabilities? Should analyze.

Keith: Some standard method for science yield. Cost estimates given to CATE. They can spell out deltas from one end to the other for us. We’ve agreed to join the tech teams.

Aki: But it’s harder on general astrophysics to get consistency.

Marc Postman: Would LUVOIR design the same 6.5-m as HabEx (question Aki posed earlier)? Exoplanets prime driver for HabEx with astrophysics on for the ride.

Aki: Given same instructions…

Marc: Given same instructions, I think we'd come to same design. But right now we are not operating under same instructions. We're all really motivated to see some capability for both exoplanets and astrophysics science.

Scott: One minor comment is that I don't like it when it's phrased that general astrophysics just along for ride on HabEx. It is a priority for us. It's not descopable in my opinion.

Marc: Good to hear.

Scott: Whatever joint appendix we do, should make sure it has same words and same typos (laughter)

Question about how to show this to community.

Scott: We can make a pact that whenever HabEx and LUVOIR are presenting, we present in a way that it's a continuum and the story fits in the same way.

Aki: Other points that keep coming up are common tech issues, e.g. UV and coronagraphy, coronagraphs and telescope stability. Joint slide needed?

Shawn: One other point. One reason to study 6.5-m and 9.2-m is Webb. Interest from many sides to study 6.5-m for that reason. Good for people doing LUVOIR to also study 6.5-m.

Matt: Joint study would be great but no time.

Shawn: Not talking about detailed.

Matt: Superficial look still hard.

Lee: I think in areas most uncertain on cost (starshades and large telescopes), if we don't present a united front … (something I can't hear).

Aki: We can't be contradicting ourselves for the next two years. We don't want to set impressions now that turn out to be wrong. We should come up with joint slide on what we should all say about cost.

Brad: If LUVOIR costs less than HabEx, then we've screwed up.

Lee: A 9.2-m room temperature telescope with coronagraph is not obviously more expensive with a 6.5-m with a starshade.

Shawn: How about "likely" more expensive

Aki: Maybe answer is none of us really know

Scott: At least from what I heard about LUVOIR architectures, it'll be more expensive.

Brad: It likely will be. I think that's fair.

Aki: Cost especially pertinent for LUVOIR; there's a fear it'll be really expensive

Lee: Expensive is relative.

Courtney: Can we say we're exploring a range of options to provide a diverse range of price points for decadal?

Scott: But people say "Isn't it going to be X billion dollars?" People always say LUVOIR has to be more expensive than JWST. I don't know.

Aki: One message we got from telecons is that mission costs are not intuitively scalable when they're very different from each other, e.g. cold JWST versus warm LUVOIR.

Matt: Why not answer I don't know?

Aki: It doesn't satisfy anyone.

Matt: Right but it's the right answer.

Shawn: I don't know but that's the point of these studies. Just wait.

Scott: Maybe this is right approach. I don't know. What does Keith think? Based on our lack of knowledge, they have already made up their mind about the mission. The longer we let them keep that in their minds, the more entrenched it gets and the less likely they will change their minds.

Shawn: Can we say these points are why it's complicated?

Scott: Can we say these are reasons why we don't know and why you should doubt your internal religious conviction?

Aki: Getting CATEs in study before Decadal? Still TBD by HQ?

Julie: No. CATE going to happen after Decadal by Aerospace Team B.

Aki: Is Paul still negotiating?

Michael Garcia (NASA HQ): Decadal obviously has to do one. My understanding is there'd be something like a CATE before this stage. This is why Aerospace is working with you.

Shawn: Both teams doing internal cost estimates?

Aki: Yeah.

Shawn: At that point, there'd at least be an estimate.

Aki: But they don't satisfy desire for consistency.

Julie: Nobody will believe it anyway. You have to wait for CATE.

Brad: I want to know if we decide to cool telescope does it really double cost.

Shawn: There's "I don't know". There's the CATE in terms of trustability. As these studies progress, even if we don't get CATE, we'll move further from "I don't know".

Aki: What does Keith say?

Keith: I don't know what to say at this point. We're going to continue ghosting the CATE. I've had Team X's on telescopes with starshades that gave the same cost number as Aerospace. Three estimates by groups with no dog in the fight gave the same number. I kind of believe it. Silly to go around talking about cost estimate that we think is real cost. But CATE is only number that matters in the end.

Scott: I agree with that. Ultimately, CATE is the only number that matters. But also concern about rest of astrophysics community when they ask these questions. What do we tell them now?

Aki: Are you ready to tell what 4-m HabEx costs?

Lee: When I joined JWST, budget was 1 – 2 billion $. That early, you had no idea of the unknown unknowns. All the risks and unknown unknowns eat your lunch by a factor of 8.

Brad: This exercise is to identify techs that we have to do better on to get better idea of what mission will cost.

Lee: But well beyond tech. Risk is hard to know. We're Powerpoint-ing at an early stage.

Scott: We get asked about cost at many conferences – every single time. We are asking. I just don't know. What do I say?

Lee: What if we bring in industry of people who build large telescopes and have them do independent risk assessments?

Aki: We don't need to write a consensus statement right now. But does everyone think we should have one? About cost?

Brad: This is something we're working on and premature to say anything.

Aki: This is a question with a yes or no answer. Common statement on cost?

General agreement.

Julie: As long as it says “I don’t know”.