LUVOIR Face-to-Face STDT Meeting Notes

May 9 – 10, 2016

Recorder: Giada Arney (U of Washington)

Day 1

Crystal: Welcome address. “This will produce transformational science that is going to be a benefit to whole world. I can’t wait to see final product!”

Brad: “Keep the LUV in LUVOIR” bumper sticker! 1st presentation by Paul Hertz by astrophysics division at HQ. Will tell STDT what he wants from it and give opportunity to ask a few Qs.

Paul Hertz: Welcomes everyone. “I’m not playing favorites.”

Paul: (slideshow NPD directory welcome)

- The Qs we’re trying to answer = same Qs humanity has been asking for 1000s of years.
- Large missions from past decadal surveys = transformational missions
- 30 year roadmap
- Excited by community support for STDTs (400-500 applications for STDTs)
- Wants to see 4 compelling studies at HQ. Decadal survey’s main recommendation = which decade will we do these in. “This isn’t a competition.” Decadal survey = prioritization of mission order
- NASA will NOT build mission described in decadal survey. Historically, most of them descoped (Except WFIRST “upscoped”). STDT to provide “notional design”
- Brad and Debra in charge, not NASA

Questions:
Brad: If we come up with notional mission that’s to be launched with SLS block 2, are we shooting ourselves in foot? Decadal not going to put priority on tech that does not yet exist?

Paul: Whether it’s good idea to use SLS, broad range of opinions. By time of decadal survey, SLS will have flown once or twice. If SLS has troubles w schedule by 2020, probably won’t look so smart to build SLS. If SLS key to heavy lift and looking good, a viable option. Don’t try to 2nd guess politics at this stage. Figure out requirements and use launch vehicles that use your requirements. Agency counting on next generation of launch vehicles to service space station. “NASA is committed to SLS, so use if needed.”

Daniela Calzetti: (online) If team decides to get community input, can we do that for specific science questions?

Paul: Yes, this team is empowered to create its own working groups, task forces, etc. You can reach out to community.

Mario Perez (HQ program scientist for LUVOIR): What's your vision of international collaboration?

Paul: Large missions can't be done in isolation. I extended invitation to international agencies to join and observe studies. Each agency chose studies they want to observe. International participation is needed.

(Chairs welcome)
Brad: I extend welcome from us. 3 interesting and productive telecons so far. Lots of work already done (e.g. HDST). We need to leverage work already done. Take science cases already out there as basis for notional mission. We should adopt some baseline aperture, what will be high priority instruments, define their characteristics, see we can meet requirements of science already essentially prioritized by previous studies. By end of year, I want to release what we've done so far to community and ask "Have we left any science behind? What do we want to do that is not do-able with notional mission already outlined?" → Have session at AAS winter meeting with interaction between STDT and broader community.

Debra: "We have some great history. Let's dig in and see what's been done." Hopes that our ideas will be so big that ultimately team has to scale back. "We should be thinking big, out-of-the-box." Need good group dynamics. But also don't just agree just to be agreeable. Come up with something grand, beautiful, magnificent.

Brad: Need participation of all. Everyone was hand-picked for what we thought you could bring to LUVOIR. Speak up when you feel need, never hesitate to do so.

Debra: We need to lower barrier that holds back young people from "those in ivory tower."

Illaria P. (online): Wondering about the approach we want to take. It sounds like the plan is to start by deciding baseline for aperture and go from there. Wondering if it's instead useful to look at science questions, prioritize them, and start from there (instead of starting from an aperture size).

Debra: Brad is suggesting start from notional idea about what telescope will look like. But all of that will be revised as we look at science cases.

Brad: We will have breakout sessions to decide science goals. That will drive us right away to aperture we need. We should be very sure of capabilities we're going to provide.

Aki: (slideshow on "What is LUVOIR and where did it come from?")

- Harley Thronson article in JATIS looks at 30-year history of a mission like this.
- LUVOIR first mentioned in last decadal survey
- Exoplanet science and broad range of cosmic origins science called out in last decadal
- COPAG report also called out LUVOIR (2015 Large Mission Report).
- ExoPAG interested in looking at both large and small apertures.

- 2015 HDST report: glad solar system mentioned; "Usually gets neglected"
- Dual science goals: Habitable exoplanets+biosignatures. Also wide range of general astrophysics (more so than specific science questions in this area). HabEx focus on exoplanet goal and make "best effort" on cosmic origins science but it won't drive major mission requirements. Solar system part needs more work.

Questions:
Debra: Is LUVOIR 100 year telescope? Serviceable?

Julie Crooke: Requirement that all large new mission must be serviceable.

Paul Hertz: There is a law that all large space telescopes must be serviceable. Worth thinking about how we leverage the investment in a large telescope for much longer than it would have lasted without servicing. Kind of servicing HST had not available; that infrastructure is gone. Serviceability means a modular design that can possibly save money. If serviceability becomes possible, possibly in private space sector, we can take advantage.

Marc Postman: HabEx will attempt habitable exoplanet goal, but LUVOIR will get a much a larger statistical sample and can actually address question of habitable exoplanets.

Aki: Personally I tend to agree but I want to point out that for exoplanets community, even a 4 m is a big advance over nothing. Never had a mission optimized for this kind of work.

Illaria (online): Is HabEx only focused on exoplanets or also cosmic origin science (COS) related to exoplanets?

Karl (joint member): HabEx team hasn't had face-to-face meeting yet. Scott Gaudi made clear in ExoPAG report that COS has to be enabled with HabEx. Agree that need to optimize sample, need to go big. One thing we'll be talking about is challenge of segmented telescope vs unobscured one. Segmented is challenging for coronagraphy. HabEx likely unsegmented.

Aki: A few cosmic origins people on HabEx STDT.

Walt Harris: Question related to solar system application. Only a couple of us have done stuff with this, but our community would have a lot to say. To what extent is there cross-talk to getting this into solar system decadal survey? If you want buy in from our solar system community, you want them involved in this and on their list.

Aki: Super interesting question. Paul?

Paul: Their decadal survey comes after our decadal survey. Plenty of time to involve planetary science community in discussions of large UV-optical-IR telescope for planetary science. These divisions are useful for managing appropriated funds. My budget is to build space telescopes. Solar system budget to build missions that explore planets and other bodies in solar system. HQ would not advocate for planetary science division pay for space telescope. HST can do solar system science but paid for by astrophysics, New Horizons can do astrophysics but paid by solar system.

Karl: We should seek solar system portion and want the planetary science decadal to be aware and endorse. Last solar system decadal survey said biggest accomplishment is exoplanets but couldn't discuss because of demarcation at HQ.

Paul: This (solar system) is part of complete science case.

Karl: Can we get planetary decadal to endorse exoplanet side (of LUVOIR), not just solar system?

Brittney: We typically ad hoc existing telescopes to do solar system science. This is good we're discussing it up front.

Aki: For the solar system, its science topics are relevant to exoplanets

Debra: HabEx vs LUVOIR. Some of our "esteemed favorite" exoplanet colleagues on HabEx. Both teams considering similar instruments. We should be helping each other.

Aki: We better share work with HabEx given constrained resources.

Daniela (online, difficult to hear): Aki, we have driver mostly due to habitable exoplanets. Is there a plan to go through numbers and see where yield values are coming from?

Aki: Yields? Chris Stark talk tomorrow is all about that.

Olivier: HabEx cost box very different from LUVOIR. One could imagine that HabEx could be too focused on its science and LUVOIR may end up being too costly and may scare decadal. Good for HabEx and LUVOIR to explore things in between. E.g. smaller version of LUVOIR that doesn't do as many planets.

Aki: I am uncomfortable that we're looking at two end members (i.e. large vs small telescopes) and not continuum in between. Want to look at options in between.

Nick Cowan: Idea to have notional mission by end of year. Another dimension is mission lifetime and how long to do certain science.

Aki: To do seasonal colors? Serviceability will help and I think we're good on that front given discussion so far.

John Mather (slideshow: "Decadal survey history and strategy")
Brad: Thanks very much for joining us, John!

- Will focus on what's similar about JWST and LUVOIR ideas.
- 1995 HST and Beyond report drafted, JWST study started at GSFC
- "Next generation space telescope" → HQ directed idea
- JWST "got standing ovation" when discussed at AAS winter meeting in 1996
- Original JWST budget was half billion dollars! (Goldin challenge: 3 teams)

- International partner agreements took a lot longer than expected
- Faster, better, cheaper not feasible

Brad: Pick two! (faster, better, cheaper)

- Webb got top rating due to ambition in 2000 decadal survey. This budget was a billion dollars.
- JWST at 2000 decadal science case was “we’re going to do everything!”
- Get technology done before the design. For HST, new detectors invented on accelerated schedule.
- Still a risk that HQ could say “Go back and get better detectors. They’re still not ready.” Serviceable mission that replaces detectors is a way forward. QE of UV detectors low; still not advanced much?
- Killer app: exoplanet science; something for all astronomers (if it does everything you’ll have a lot of friends)

Questions:
Aki: Deep in my heart, I agree with your closing sentiment. Do what we want to do, let cost fall where it will. But now that NASA had JWST experience, will that affect how stakeholders will see LUVOIR?

John: Obviously it will. HST not cheap, but we made history. HST cost a lot more than it was supposed to, but people are still proud of it. In the end, people don’t remember what it cost, they remember if it worked. Don’t ask for what you don’t honestly need, but if you need big, we can do that. If you don’t need cold, don’t make it cold. If you need cold because that’s where honest science is, ask for that. Have a properly balance project. Keep looking for things that make it cheaper; modular makes cheaper. For example, if you can guarantee you don’t need to test the whole thing at once all in same vacuum tank, that would be huge. I don’t know what vacuum tank we’d fit the whole thing in.

Brad: Biggest potential landmine?

John: Great question. Not sure. Make sure to have test program properly scoped. JWST test plan changes completely; embarrassing when figured it out late.

Paul: Pre phase A, not best use of time to work out detailed test plan.

John: But at least say if need vacuum tank or not.

Aki: We don’t need lots of precision on cost, but we need good accuracy, low precision.

John: Is it testable? Do you need entire new infrastructure to test it? Can you leverage off of expected infrastructure? You can’t get to PDR level by end of this study. Be smart about where to worry about details.

Aki: Need to hear a presentation from aerospace about what we do and don’t need to provide to get reasonable accuracy

Harley: To an important degree, JWST product of Dan Goldan. Initial recommendation for 4 m telescope. Dan Goldan argued that this wasn’t big enough. Argued for twice diameter at same price (not possible). He pushed hard for this mission. One lesson is that senior administration person steps in and pushes this mission far further than science community.

John: Cooperative agreement notice total budget of 600k for three big studies.

Brad: Thanks very much. Very helpful.

Marc Postman: (slideshow: “Cosmic origins science w/ LUVOIR”)

- Can resolve size scale of giant molecular cloud anywhere in universe. Can resolve 100 pc resolution in optical at all redshifts.

Chris Stark: What are the exposure times for HST for image (shown) vs LUVOIR?

Marc: Don’t know, but for a redshift 2 galaxy, it would take minutes of exposure time for LUVOIR. With HST, you can get this image in an hour and a half.

- 1 hour imaging down to 32^{nd} magnitude for 12 m HDST telescope.
- UV science on gas requires 10m+ aperture. UV spectral features provide best constraints on ISM, ionization, gas temperature, gas density
- To get 1^{st} giant elliptical, you need about 8m telescope. For 10 or 12m telescope, you can map gas physics and star formation histories of 100s of galaxies
- Lots of emphasis on why UV is essential: you need UV because IR colors are degenerate w stellar type as a function of age.
- Can study motions of stars in every local group galaxies (transverse motion on sky to 1 km/s). Capability pairs well w ground based telescopes that will measure spectra of these but can’t get transverse motions.
- “Holy grail” is initial mass function. So far only can do for SMC, LMC, and our own galaxy. Need to get to faint stars to do this well. To get all galaxies in nearby local group down to 1/10 solar mass, need LUVOIR. Can do 100s of galaxies w/ LUVOIR. UV provides estimate of stellar mass accretion disk.
- “LUVOIR will radically advance every area of astronomy…In a way that’s fundamentally unreachable by smaller telescopes in space”
- Instrument Emphasis: UV capability, large aperture

Questions:
Debra: UV is one reason why LUVOIR different from HabEx. How far into UV to achieve science goals?

Marc: All of this we can do if we can go down to 1100 angstroms.

Lee Feinberg: Would any science benefit by pushing diffraction limit lower?

Marc: HST already shown that even though spectra on HST gets better down to 4000 A, then flattens out due to surface roughness but doesn’t blow back up to arcsec in UV. HST not designed to be diffraction limited in UV, but it still does pretty good.

Kevin France: COS-exoplanet overlap in disks, stars. All these same tech capabilities allow us to address.

Marc: If you're at a kpc, you resolve down to an AU.

Kevin: As I was reading materials, only cosmic science case specified in ExoPAG case was stars. Don't forget other things like disks! Lots of technical advances for mirror coatings, etc.

Brad: Useful to have joint meeting with HabEx about technology. Things of mutual interest.

Walter Harris: We talked a lot on HST about pushing diffraction limit down in UV. On subject of coatings, I agree. We still run into issue that we have to get it into detector. Have to look at windowless detectors. Looked at coating mirror segments w/ different things to push down into UV.

Daniela (online): One part of COS not represented = sources of reionization? (hard to hear) We need larger telescope than HST (6-8 m moreso than 20 m). Fundamental question is what ionizes universe? What are assumptions in gas structure? (referring to simulations shown on slides)

Marc: That map doesn't use quasars, you're detecting the hot gas. This is the faintest light in the universe and only a big telescope can detect it.

Mark Marley and Vikki Meadows (exoplanet slides)
Mark: I will do non-habitable planets. Vikki will do habitable planets.

- We understand habitable planets if we understand context, diversity of planets in the system.
- Great thing about Kepler is discovery of diversity of planets, including super earth, sub-Neptunes
- Huge diversity in smaller worlds. We don't understand them. Huge opportunity to characterize a whole new set of worlds.
- Mentioned hazes and how they make transit spectroscopy difficult → that's why direct imaging so important! (Caroline Morley's work)
- WFIRST coronagraph = technology demonstrator; only 1 year in nominal mission devoted to coronagraph. "WFIRST is not the solution to the science. We really need a future telescope"
- Giant planets easier, great targets for spectroscopy.
- Now onto the 1% planets! (laughter)
- Emphasis: Measuring properties of diversity of planets

Vikki: I'm a card-carrying solar system scientist. I started out observing water vapor and oxygen in Venus atmosphere, so clearly I like looking for these gases in difficult places.

- Biosignature false positives important
- Big huge goal: prevalence of habitable and inhabited planets
- WFIRST had to be binned down to R = 20 for sufficient signal; lose O2 band
- LUVOIR gets a broad range of planets around different stellar types
- H2O in the stratosphere is "a planet in crisis"
- H2O swamped by methane bands around M dwarfs due to photochemistry

- O_2 false positives: 3 confined to M dwarfs. Abiotic O_2 can be identified. → we want to get CO_2, CO, CH_4, O_4 dimers to identify false positives → broad spectral range needed
- Glint → crescent phases
- IWA important to consider for lower mass stars
- "The valley of death" → clobbering our shortest wavelength water band
- Time estimates for integration is PER BANDPASS
- May want to bin down resolution for distant objects.
- Instrument Emphasis: Broad wavelength range, ability to see biosignatures and false positives to distinguish need to push into IR

Questions:
Karl: Exozodi worse at longer wavelengths because PSF growing. At 1.5um, have 10x as much exozodi contaminating.

Chris S: That's taken into account in the yield calculations.

Karl: Oxygen dimer important at what pressure?

Vikki: About 3 bars. Shows up in massive oxygen atmospheres where water boiled off.

Illaria (online): Which mission will provide targets for LUVOIR?

Vikki: We're going to do it ourselves.

Aki: There is no mission. The mission that can find targets in habitable zone is the mission that can characterize them.

Illaria: Focus on O_2 and water?

Vikki: Those are high probability things we can look for. I advocate longest possible wavelength range to look for other potential biosignatures. Methane, other species in near IR. We better not build something that can't do oxygen, but keep minds open to other biosignatures.

Leonidas Moustakas: Broad UV range important.

Vikki: Absolutely. And UV helps us characterize the star.

Britney Schmidt (solar system slideshow)**:**
- Good opportunity to ground truth what's happening in other solar systems
- Ice giant characterization
- Interested in getting diffraction limited as far down as we can.
- First spectra ever of small body targets
- Establish baselines of exoplanet atmospheres (use giant and ice giants in solar system)
- Measure and watch changes in solar system. E.g. losing great red spot.
- Ice giants have strongly different dynamics than Jovians

- Tracking processes over time emphasized.
- Europa a “moon-sized planet”
- Chaos terrain regions resolvable w/ LUVOIR
- “Change detection” important for understanding dynamics in a real way.
- Surface change monitoring on Pluto; Triton. Looking at atmospheres of these objects.
- Map solar system science to exoplanet interpretations.
- See km sized objects in Kuiper belt
- Major Emphasis repeated several times: seeing changes occur on solar system bodies

Questions:
Walter Harris: I quibble that we don’t care much about high res spectroscopy. With high res spectroscopy, we can look at plasma, wake turbulence, aurorae. We want to be able to look at Venus. We need high res spectroscopy to look at super rotation, isotopic ratios in the atmosphere. We’ve been talking about pushing to shorter and shorter wavelengths. Solar system is optically thin in EUV until you hit 300 A when He stars to absorb, so there’s science drivers for UV capabilities and high res.

Brad: (joking) if you look at Venus with 15 m telescope don’t you set the thing on fire? (laugher)

Britney: I didn’t think solar system observations would drive spectral resolution. But synergy between what exoplanet atmosphere observers want and what we want. We can leverage observations of solar system objects to understand exoplanets.

Vikki: Resolutions I was showing in plots were R=70 but I hope you push higher than that. We’d probably push for 140.

Britney: High res in solar system would be awesome!

Vikki: In solar system you could go after isotopes. R=1000 for solar system?

Aki: On one of 1st slides, there something about high contrast. To see Jupiter moons need to knock down Jupiter photons to get contrast. We’ll have coronagraph, can we put thought on how well it can suppress resolved source behind the mask.

Britney: Neutral density filters, etc. We can think about these options. We would like to not have all those photons.

Lee Feinberg: This (UV discussion) sounds like a STIS instrument. Synergistic with spectrometer. Exoplanet instrument will have low res spectrometer.

Britney: For geophysics we want best spatial resolution possible. Geology, geophysics, activity monitoring.

Brad: Break for working lunch.

Debra: Cool tagline for LUVOIR: eta_life? Next term in drake equation. Want your ideas of big science goals.

Vikki: Need capability for high res on best targets and be able to bin down for worse targets. Rely on detectors that allow us to bin without penalty. Don't have that capability right now.

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SNR   |
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       55K                  300K
          resolution
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Aki: Need high resolution to get planet masses. We obviously want planet masses.

Debra: Can't get past telluric contamination. Need space.

Nick: RV from space to search for planets or characterize?

Debra: You can bin down high res spectrum from ground in software

Mark Marley: Huge uncertainty on what looking at. Gotta get mass.

Olivier: RV and astrometry can be used to get masses

Debra: Broad wavelength coverage to disentangle stellar photosphere. Can we come back to astrometry? Can do alpha cen, harder for stars at 20 pc.

Olivier: Landscape of RV and astronometry different than it was 20 years ago.

Brad: We'll have coronagraph; can't we pull out orbital motions?

Olivier: To get mass we have to reference position of star with rest of field.

Debra: If know orbits of planets in advance, how does efficiency change?

Walter Harris: How much time spent looking for Earths vs characterizing them?

Debra: We need big aperture to do follow up studies of planets (mass)

Olivier: How to make most efficient program? Can we know targets beforehand? Need many samples, measurements

David S: Many of these signals will be repeating.

Debra: Great thing about space is lack of telluric contamination.

Lee: Diachroics. Pick other bands and spend into high res spec. Want something w/ least number of reflections. Optimize throughput?

Brad: For extragalactic, we are looking at extended objects. IFU needed. Exoplanet IFU might be 10 arcsec, but one for extragalactic might be 5 arcmin

Marc: What do we do about high redshift galaxies? We know of galaxies at high redshift that get very compact, even with HST borderline unresolved. JWST will do better, UV resolution will be useful.

Aki: We don't want to miss science requirements that will drive instrument requirements What technology barriers need to be overcome?

Walter H: Laser line can do tuned high res RV. Movement of emission or absorption features of star against laser.

Debra: Problem is Doppler shifts on surface of star.

Aki: Need to resolve shape of line, not just line shifts to beat down the stellar noise floor on RV.

Debra: Advantage of large bandpass: leverage differential response.

Marc: Subset of HDST team visited JPL last September. Clever idea for instrument. Embed in wide field imager a laser system that periodically can get turned on to calibrate astrometry. They claim with this thing you can begin to think about nanoarcsecond astrometry. If true, revolutionary game changer.

Olivier: Bright stars would saturate such a detector.

Marc: I'm thinking about dimmer objects (galaxies)

Aki: There's a talk tomorrow about general astrophysics we can do in 2030s. Will talk about giant segmented mirror telescopes.

Lee Feinberg: We need to build telescope with picometer stability for high contrast. Multiple layers of mechanical isolation. Surprised at how good line of sign numbers are with really good isolation systems.

Olivier: Coronagraph requires stability on short (hours) time scales. Astrometry requires stability over longer (year) timescales.

Karl: Astrometry comment. Need signal to noise of 10^6 to get this. Not sure how far we can go w/ this in extragalactic realm.

Leonidas: At splinter discussion, we will just begin to outline primary themes beyond JWST, WFIRST

Aki: Draw distinction between science goals (big picture questions) vs science investigations (projects). Incomplete?

Kevin France: They've been presented, but I don't know we've seen all of them yet.

Nick Cowan: Drivers on telescope. Does tech for exoplanets carry over to debris disks, etc? Anything you want that exoplanet direct imaging people who want fully formed systems don't emphasize?

Aki: UV, OWA. Some of most interesting planet formation work not with coronagraph but with spectrograph. We won't beat ALMA.

Brad: IFU appropriate?

Aki: Might be…

Kevin: We can get smaller scales.

Karl: Disk science case more for debris disks where ALMA not contaminated

Kevin France: If want to know composition of gas in protoplanet disks need to do spectroscopically or not at all.

Aki: How much will be done with JWST?

Debra: This was a good warm-up

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Aki "Why what how?" document
Explain what science goal is and why we care? Accessible to general reader or stakeholder

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Exoplanet breakout

- Very important to get extremely high resolution to do RV. R=150,000
- ELT in NIR out performed by LUVOIR in NIR
- Simultaneous UV, optical, NIR needed?
- To wash out photospheric noise sources, do need simultaneous bandpass observations
- How many simulations needed where knowledge is incomplete?
  Chris Stark: Monte carlo simulations. Design observing plan.

Compare efficiency for finding vs characterizing planets

Aki: Bandpasses to filter planets, galaxies, background stars. Stars and background galaxies don't have strong absorption features at 1 um.
Vikki: 1 um is a problem (the "valley of death" for detectors)
Olivier: THEIA (telescope for habitable exoplanets, European mission)

- Simulations can show how much we can save in terms of planet yield.
- For coronagraph, total time spent characterizing is small fraction of total time of year.

- Precursor mission makes sense if planets we care about are rare. If we love all planets, precursor mission not as important.
- Get spectra of ALL planets in system for free, including time we spend searching for Earths
- Size-albedo degeneracy. Mass is the only way to determine if it's really an Earth. We have to characterize the planets before we know what we're looking at. Spectrum is expensive; we want to know what size planet is before we take it.
    - Tight IWA (crescent phase)
    - Rotational variability, spectral variability
    - Consider albedo (reasonable albedo range for habitable planets)
        - Wouldn't want to consider habitability just based on these
- Technology has moved so far that astrometry and RV can be done in space much cheaper than before. Completely different background from SIM.
- Technology has gotten much smaller
- Need for preliminary mission?
- LUVOIR has to do either astrometry or RV?
- Early Earths
- Eta_habitable; what has water? What has tectonics?
    - With a large enough statistical population, we can measure eta_whatever
- What will give greatest statistical probability of finding an Earth?
- Looking for Earth as it looks today a more defined question than looking for habitable planets more broadly
- Eta_solar system
- A habitable Earth that is completely unlike ours would be a huge discovery. Finding an Earth twin unlikely and doesn't each us as much as finding a planet that's habitable and unlike Earth.
- Decrease ignorance on eta_life at least
- What does "habitable" mean in the context of what we're looking for? Earth-sized planets with liquid water?
- "Getting to know the neighbors" → survey everything nearby. Learn where Earth sits in the larger picture. Answer question of are "Earthlike" planets common?
- Kepler confirmed the planets are there. Next step is to figure out what they're like.
- If we can find Earths, we can find all the other easier (larger) planets as well.
- How far into IR can we go? (would like to get into K band). 1.8 um not too hard. Farther than that is difficult.

Molecules we want to detect:
CO: 2.3
CO_2: 4.3
N: 4.2

- If we let telescope get below freezing temperature, drives up test costs.
- IR: Also a problem of IWA not just thermal background
- Pointing jitter not as bad at IR wavelengths.
- Finding for technologists: Find a way to get to 5 um.

- Trade off: We can get to 5 um potentially, but # of stars around which we can characterize planets at 5 um is very small. In NIR, might need to move to starshades to do characterization.
- Starshade for simultaneous IR can get colors that show rotation (continents)
- Coronagraphs can characterize orbits, starshades can't
- UV coverage important (this has been repeated multiple times today)
- Solar systems at 3 um is hugely important (organics, ices on surfaces)
- Temperature stability
- HST has a coating that works from Lyman alpha to 5 um. What is throughput over this range? What kind of bandpass can technology folks build? If loss of bandpass significant, it's like cutting down aperture.
- Magnesium fluoride coatings
- Breakpoint at 1100 A in mirror coating tech. Shortward loses performance in optical.
- Three coronagraphs for different wavelength ranges (UV, optical, NIR)
- For planets, NIR more useful for characterization than UV for planets. UV important to characterize the star.
- UV dropoff can suggest the presence of an atmosphere.
- Characterizing the UV flux of the star is critical for understanding the photochemistry of the planet. UV characterization of star very quick.
- Internal coronagraph: speckles brighter at shorter wavelengths
- Ability to use multiple instruments simultaneously very important.
- Coronagraph in parallel with stellar characterization.
- Measuring beyond the orbit of Neptune, inner Oort cloud, "planet 9" "Probing the icy frontier"
- System architecture (of exoplanet systems) drives OWA
- Space weather throughout the solar system
- Star-planet interaction the biggest thing that affects habitability
- "Living with another star"
- How close can we observe to the sun? Can we see Venus?
- Brightness limit? (neutral density filter, subarrays)

Post-breakout session
Debra: What brightness limit is feasible? (1100 A – 5 um). Different channels for UV, optical, IR (diachroics)?
Lee: Al-Fluoride? Any instrument can have UV throughput. Visible instrument silver.
David S: Silver is a better coating but then you can't get into UV
Lee: Wide field instruments in visible w/ silver

Notes from Adobe Connect session:
UV observations
- What UV coatings?
- In UV, can't get a large field
- Wide field aberrations

Widest FOV at prime focus

Parallel observations wide field imaging of field; can be efficient for collecting data; scattered light is a concern; need to worry about where to position the camera

Need for very smooth mirrors

How do mirrors age?
- Micrometeorites? -> small throughput loss over time
- Do pits (from micrometeorites) in primary mirror affect scattering in coronagraph?

For long wavelength end, at what point do we need to cool the telescope? We are also limited by IWA, not just telescope temperature.
- 1.7 um (Wide Field 3 instrument); room temperature blackbody curve starts to swamp
Telescope kept at room temperature in space. (baseline)
- Si Carbide lines to be cold
- There are documents discussing telescope temperature, materials that perform well at different temperatures

picometer stability is a difficult problem. "the picometer problem"

Sunshield (JWST-type) preferred over light baffle (infield stray light)
- Stability? Radiation pressure?
- Key issue is offset of center of gravity

Long wavelength cutoff: there are interesting molecules (e.g. CO_2, CO) beyond 1.7 um. What is the shortest longwave cutoff we can live with?
- Targets we can go beyond 1.7 um will be brightest ones due to IWA. Maybe we can tolerate more noise for these targets.
- It takes a lot of temperature change to enable observations at 2 um
- Thermal background drives the cutoff (temperature of the primary mirror)
- What sensitivity do we need at the longer wavelengths?
- at very high resolution, can we get around this issue? (Snellen technique --> ground based moving in this direction; using differential RV between atmosphere and target; maybe in space we can use to remove thermal background)
- science cost to going colder if it degrades coronagraph
- chromatic speckles

Need longer IR measurements > 2 um to find biosignature false positives/other molecules to understand planetary context/comparative planetology (CH_4, CO_2, CO, O_4 dimers; N can be seen at 4.2 um and can help constrain atmospheric pressure -> rule out "Wordsworth + Pierrehumbert" false positive)
- can we find a place between "are these biosigntures?" and "that's life!" ?

Longevity of this telescope?

For longer wavelengths, switch to different starlight suppression tech? (starshade? --> higher throughput)

Longer wavelengths may only be relevant to the nearest targets

Cold "seasons" for telescope? (where it's allowed to drop in temperature)
- Affect UV astronomy (contaminants?)

- If it's allowed to go cold at any point, we have to test it on the ground (big cost increase).

All of the false positives we've discovered were recent! Level of trust that we know what all the false positives are. Need more contextual info on planets. -> driver for extended wavelength range
- Have to understand the environment to understand what we're looking at
- Greenhouse gases in atmosphere (CO_2 at 1.6 um, 4.2 um)
- Need UV measurements of host stars to understand photochemistry on planets

Goal of LUVOIR to make statistical sample of planets

What is the trade space? (e.g. monetary cost vs science cost)

Cryogenic cooling testing on ground huge cost driver for JWST

Creative observational techniques vs actually cooling the mirror?

Only working with starshade -> no picometer requirement.

What are everybody's top level science goals?
- e.g. cosmic origins has to have UV
- If you make telescope cold you MAY lose UV capability

Day 2

Debra: Welcomes everyone. Homework: read up on your favorite science case, generate a "killer plot" on how LUVOIR changes field, write up technical requirements on how to do what you want to do. Feeds back into instruments. E.g. What FOV, what bandwidth, what instrument.

Kevin: Does this mean filling out Aki's form?

Aki: It can be. We'll come back to that document later today.

Debra: In a bit, we'll go around the room and have a poll on what we want accomplished by the end of the day. Please express concerns about how process is going but remember this is the 1st face-to-face meeting. But first, I want to hear from Julie who will tell us about our tlimeline.

Julie Crooke: (slideshow on study plan and schedule)

- Study office: study scientist, study manager, science support analysis team, etc
- IDC = integrated design center
    - Optical design lab, instrument design lab, mission design lab
    - Conceptual design is done for EACH instrument and the telescope
- This is an iterative process (not one time in, one time out)
- Two years from now, need to be done
- Need to potentially fit into a number of different launch vehicles
    - Being able to fit into 5 meter fairing not "risky" to the decadal survey
    - Needing to use SLS = potential risk

Debra: Maybe not everyone knows the limit for a 5 m fairing is a 9-m telescope. When doing your assignments, suggestion to compare a 9m telescope vs. a larger one.

Marc: That 9m limit is based on JWST.

Lee: We did package a 12 m, but it was really challenging and only had a couple tiny instruments.

Debra: We can define how science case would be impacted by these different apertures.

Julie: I can't say we can for sure fit three instruments in the 5m fairing.

Lee: And a lot of it is determined by size of the instruments. Wide field instruments are huge.

Julie: Block 2 A is 8.5 m fairing, Block 2B is 10 m (?)

Chris Bolcar: Block 2b more powerful. Unclear which one they're going to build.

Aki: We have the Tech Note done on the launch vehicles already.

Marc: Mentioned SLS could be perceived as risk, but launch date is 2035. What is average lifetime of any given rocket? If we say Delta-4 heavy to be safe, isn't it a risk to assume it'll exist in 2035?

Julie: That's why I call it a 5m fairing not a particular rocket. But you're right. We don't know what will be available. Safe to assume at least a 5m fairing.

Nick Cowan: Question about telescope origami. Largest diameter we can fit is proportional to what geometry of fairing?

Lee: Best to show pictures. Turns out height of secondary is a player in this. But a 9.2m telescope fits comfortable in 5m fairing. When go to 8.4m fairing, even lowest mass SLS, you have enough volume for 12m telescope. NASA has been working on this a while.

Debra: Will we know more in 2018?

Lee: Not much. The issue is the big fairing. The competition is the SpaceX strategy of smaller, re-fuelable rockets.

Shawn: This is type of thing it would be good to get interactions with Aerospace on.

Lee: Other thing is to explore is idea of launching in couple pieces. We saw yesterday how you can dock things. If you really want 15 m, backup plan is to launch in two pieces. Can we launch twice?

Brad: I asked Paul about this, and this caught him by surprise. He said one if it's an SLS and maybe a second if you want a crew.

Debra: But he also said to think big and develop out of box science cases.

Erin Smith: Make science case for big telescope, big aperture, we can do it with SLS. Have optimism that we'll have a great rocket. If we don't have that rocket then we say, "These are our options. We can go with a smaller fairing. Or out of the box, what if we assemble it in space?" Throwing that on table at decadal, that's where you do it. This is an opportunity to think about crazy ideas for now, but in future there will be a paradigm of in-orbit assembly.

Brad: There's a precedent. Space shuttle and HST were designed together. HST was originally going to be 3.6m and was scaled down to fit into shuttle, but shuttle made as big as possible to take biggest possible telescope into orbit. If we want a Block 2 fairing, we're a customer.

Chris S.: (comment I didn't catch)

Britney: Planetary community has realized that strapping yourself to SLS cost could be a problem.

Julie: SLS is not costed in science directorate. With Hubble servicing, launch vehicle infrastructure is paid by human exploration.

Brad: Another reason to pay attention to human spaceflight and its possible role.

Shawn: Advantage to this is scalability and flexibility of this architecture of launch fairing or rocket because we have a lot of options. There's a sense we should be ambitious and big and talk about SLS. But to mitigate total risk, keep option open for smaller fairing. And other reason is what Olivier mentioned yesterday: the bigger we go and more ambitious we are, the more important it becomes to have interpolateable size options between LUVOIR and HabEx.

David S: How do we bring industry into it?

Julie: Good question and we so badly want to bring industry in. Up until decadal, there were resources to send CANs to provide cost sharing to industry to allow industry to say "NASA is really serious about this! We can really make investments!"

David S: What can we do now?

Aki: With resource situation what it is, we can't do that right now.

Kevin France: How much more do we need?

Brad: We have been pushing back at HQ on what they've given us to do what we need to do. This is still a ways down the road and we'll keep proceeding.

David S: There's not much time. We need to bring industry in now.

Kevin France: RFIs?

Julie: Industry is not in same situation as 10-20 years ago when economy was bigger. Industry is struggling to throw money at this. Alberto or John, comments?

John Arenberg (Northrop): We have responded to one RFI from one study team.

Debra: Which team?

John A: X rays. They asked for help on mirrors. That's one method to collect ideas. If people have good competitive idea, they won't just give it away. Some small amount of CRAD that can be matched, not quite CAN study, is possible. There are two companies at this meeting. There is interest, but it's moderated because target is so far down the road. I have to make a business case to spend internal resources and I have to make case against sooner targets. But RFIs will get responses. Think critically about what you need from industry. Not instrument design. Traditionally, that's done by scientists partnered with industry. But optics, infrastructure, sustainability, etc done by industry. Ask the right question.

Harley: Two or more industry days are being set up in next couple months for STDTs. We'll send reps for industry days.

Julie: Doesn't address lack of resources.

Harley: But you can still address industry in detail.

Debra: All four studies are constrained in terms of budget. We are not at a disadvantage compared to the others. We'll talk to other STDT chairs.

Shawn: One online question.

David Redding (online): I heard SLS cost not assigned to LUVOIR. True?

Brad: Correct.

Shawn: From **Illaria (online)**: Request to be explicit about what it means for fairing and instruments.

Matt Bolcar (study office technologist slides)
Instruments – priority:

- High contrast segmented coronagraph – high
- Deformable mirrors – high
- Ultra stable systems – high
- Starshade – high/med
- Vis-NIR detectors for exoplanet science – high/med
- Mirror coatings –med
- UV detectors for general astrophysics – med
- Wide band vis/NIR detectors for general astrophysics – med
- MIR detectors – med

Shawn: Question from online: Do deformable mirrors include deformable primary sections.

Matt: Yes it does Dave.

Shawn (relaying **Dave Redding**): Dave says "woohoo!"

Aki: When is this deliverable due?

Matt: Technically O1 tech deliverable due June 30. I am shooting for June 1.

Debra: HQ sent email correcting it to June 1.

Karl: This is preliminary tech list. We can do it over again. This is your chance to get into current budgeting cycle for tech investment.

Brad: I'd like UV coatings bumped up to higher priority. Sensitivity to 1000 A very important. We will lose science in cosmic origins if we don't. Also, every time we mention servicing and serviceability everyone nods.

Marc: I want to echo Brad. Starshade for 10m or larger is unlikely option. If you look at it, starshade for this big telescope has to be 90-100m and flies at distance of 150,000 km away. UV detector and mirror coatings are high priority.

Brad: Starshade is an enhancement.

Matt: Starshade is enabling if we find we can't do coronagraphy.

Aki: No one is giving up on coronagraphy. If it doesn't work we need a backup option. Does Northrop share Marc Postman's assessment of starshade?

John A (Northrop): No, but it bears critical study. We will hopefully demonstrate one with WFIRST that drops the risk. Now it's only a factor of three change in size. This observatory will do other things while starshde is maneuvering.

Debra: Sounds like RFI!

Aki: I've heard a lot of uncertainty and anxiety about UV coatings.

John A: Something to go along with coatings ("clean materials"). One thing to make them work but all this talk about warm telescopes makes me nervous and worry about outgassing especially if we talk about 50-100 year lifetime. Most current materials don't degrade over time.

Norman: JWST is cold and has composites.

John A: JWST is very clean after launch. All accumulation on mirrors prior to launch. Mirrors warmest thing in space. JWST fitted with trap to collect outgassing. Net accumulation on mirrors on order of Angstroms after launch. If you have warm telescope, this is a concern.

Aki: This is getting too detailed now.

Lee: We understand how to deal with this. Real tech improvement is to get to 900 A without Li Flouride. We have an aluminum added fluoride that can get 100 nm reflectivity and doesn't appreciably appreciate reflectivity at longer wavelengths. There are a couple other options. On starshade I want to make comment, when we looked at it for HDST, it's a pointing time issue, but there's a middle ground to stop down part of primary mirror (eg to six meters) to have smaller, closer starshade. Good backup plan. Issue is how long it takes to repoint.

Norman: Servicability isn't on this list (slide). How will servicing modify what we have?

Brad: We can upgrade detectors.

Olivier: To respond to Lee, I get nervous when we talk about using partial area of primary. Logical conclusion is why don't you build a smaller telescope.

Lee: Wasn't advocating this.

Norman: This is how we manage risk.

Shawn Online question: Any question on metrology? Do we have to pay for servicing?

Debra: Yes we can service, no we don't have to pay for it.

Matt Bolcar: Metrology we've considered.

Walt Harris: I want to suggest minor change. You break out Vis/NIR detectors for exoplanets, but most of the problems we will have are for all targets. I'd include UV detectors. There's no way we have existing dynamic tech to take full advantage of UV. We'll saturate existing technology at this size range.

(Polling everyone on science goals and what they want accomplished at end of the day)

Debra: Let's poll everyone on goals at end of the day. I want to prioritize notional instruments. These will be refined by HW assignments. For exoplanets I want to see top 3 science cases, how to engage community, maybe start with HDST team. Consider hard stops for instrument design. E.g. coatings. We heard from Lee that going beyond 1.7um is a hard stop. We have to make design choices here about science we do. There's a hard stop around 1100 A, 1.7 um, FOV issues, maybe magnitude issues. Maybe we need to define tech focus groups.

Courtney: We discussed different designs and 3-5 instruments, but I don't know how much capability you can cram into one instrument. On science side I want to understand sample of stars we look at and understand switching from starshade to coronagraph regarding how much sample is lost.

Lee: Two things. One is astrometry question. Was looking at pointing line of sight predictions, we're in microarcsecond, so worth working out what's worth doing astrometry-wise. Other is RV question of 300,000. Interested in working out can we do it, what does it take, laser tech?

Kevin: Come back to making sure to emphasize UV detector issue. Something Walt said struck a chord. We still have factors of several to gain in QE and this is only wavelength we can do it in. We're not developing single detectors but some sort of tiled array but no one has tried to do. Dynamic range in UV is huge. In HST we can't observe UV bright sky.

Debra: Probably our next face to face will be in August. Let's talk about setting up tech focus groups.

Kevin: And one science thing, I'm heartened to see we've grown to 18 m! (laughter) Let's think big as possible but know why 12 not enough and why has to be more than that.

Olivier: General comment. Risk that if we too quick select instruments we may miss science opportunities. Want all to think outside the box. We got thinking about astrometry, extended wavelength. Parallel to thinking about instruments, all think about what kind of science you may not be familiar with we can do with this aperture. Besides notional instruments, there's a risk of only thinking about science done with instruments and not telescope.

Walt: All the items on the list (slide) will take a while to define. We spend a year considering tech on HDST. Requires face to face meetings to decide on killer apps, top level science drivers in each area. Great to come away with top things in areas we want to understand.

Mark Marley: Yield(?) in exoplanets so important. Devil is in the details. HabEx will look at in great detail. What is our plan?

Aki: I want to see 6-7 versions of science document that I showed yesterday. I want breadth to the science, not depth. That will assist us in throwing out what kinds of instruments and capabilities we are most interested in. Shallow breadth needed on science objectives.

Brad: I wrongly assumed we'd have greater familiarity with HDST coming into meeting. Going back a level, I don't want to talk about specific instruments but instrumental capabilities. We've considered, low res, med res/high throughput, high res instruments. What needs these capabilities?

Julie: Pass

Vikki: Thought your goals are great and ambitious given time today. Personally I want to look at whether we need a colder telescope and tradeoff between IWA and spectrum we can obtain for a range of planet targets at different distances.

Leonidas: Maybe we should have done our HDST homework! I want to understand breadth of science goals and how to push our capabilities.

John O'Meara: I want to create science working groups for each section. I want a point person in each section (solar system, exo, COS, tech). I want four working groups with leaders by the end of the day. We can make a killer plot in a week or a really awesome plot in a month, and to do the latter, we need science working groups. Also if you want a bumper sticker, send me an email! Also I want to advertise there's a suite of performance graphics Jason Tumlinson has put together that will be useful.

Marc: Want to identify are there simulations we think we need. That may take several months. Making amazing pictures about how LUVOIR will observe will be a lot of work. We can bring in folks not on the team who still have skills to help us.

Laurent (bit hard to hear): Two questions on exoplanet side. On science side, there's question of the science capability. Will we have precision RV when we launch? Kuiper Belt, solar system capabilities?

Debra: In other words, what precursor science will make LUVOIR more effective?

David S: Signing off on this list (on slide) very important. In terms of things we think are driving factors. If we really want this to be successful, we need to get started on these things yesterday (laughter). I think we can think about other instruments, filter sets, but that won't determine whether we have a credible mission at end of the day. Let's not lose sight of top 3-5 items. To echo Marc, we need support for simulations and calculations. Working groups should focus on how we can pool our resources. Only so much we can do individually. Also important to go come up with rough hard stops.

Debra: Good point. Lots of people want to be on team but didn't make it, but they are happy to join science working group.

Britney: I want to know what the bounds are on wavelength range and resolution. That drives what we can do in solar system and how that couples into science being done by other groups. E.g. if important from cosmic origins perspective to understand ice line, that has different implications in solar system for what instrument has to do and the wavelength range. What are driving measurements for certain groups so we can figure out how to contextualize solar system? What are drivers on both short wavelength and long wavelength end? What is degree of hardness of these hard stops?

Debra: Cold vs warm telescope very important!

Illaria (online): Want to identify key questions in different science topic and figure out which are the driving ones. Also identify working groups.

Dave Redding (online, via Shawn): Respond appropriately to O1. Also want clarity on IR with respect to spectroscopy. Keep open cool telescope options. Supports Olivier with respect to science like astrometry.

Karl: Agree with John to organize working groups today. What do STDT members want to work on? What do we have expertise on? What do we need outside people on? I'm worried about technology urgency issue. We have made some progress since 2009 tech report, but still no lab test of segmented telescope with coronagraph. Keck is still high contrast demonstration. HQ not providing enough money, so if concerned, there should be expression of concern from group as a while.

Laurent: Business as usual (re. budget) not going to work.

Marc: Yes and if colleagues try to convince you that best strategy is to submit tech development plan in 2020 it won't work.

Karl: Courtney's question about targets: I have a chart that will clarify that.

Daniela (online): Agree that we should target on science questions first. I want to be on (lead?) working group? (difficult to hear)

Nick Cowan: I agree with Mark Marley's concern. For today, I want to talk more to Mark and Chris Stark about survey strategy. Not clear to me how to actually find planets. It's not trivial.

Marc Ferrari: I want idea of tech capabilities of instruments. In France, I will have to start discussion with my colleagues on tech development. I need idea of tech requirements and specific capabilities of first idea of the instruments.

Antonella Nota: Most of my points already made. Starting working groups, defining science case. This is time not to leave any stone unturned. We need to present most comprehensive case we can.

Debra: If everyone reached out to 5-10 people on their favorite science questions, we can start to compile a massive and broad set of science cases.

Deborah Padgett: Far IR STDT already broken up into working groups and invited external people. While all here together, in cases that push hard stops, we need to talk about them.

Susan Neff: I echo that we should use community resources. Not just people who applied to STDT.

Kevin: I want to add, based on what Mark and Aki said and discussion with Mario yesterday in brining in international community. I've been talking about LUVOIR for two years now. Let's have elevator science pitches in some document so that when we're trying to get people outside of the US excited about this, we have something.

Harley: Strongly emphasize what two Davids and I think Mark said. What you hand off to technology management, I urge a small number of tech recommendations. Larger list of tech prioritization, the more useless it is. It's too much work. Limit it to three. Next tech prioritizations have reduced availability on time.

Antonella: Barstow is organizing something (meeting?) for international observers. (hard to hear)

Shawn: Thinking about HabEx having STDT next week, let's have a list of things we want to start reaching out to them for.

Brad: Neither of us can do enough instruments. Let's talk about joint funding of instrument studies.

Aki: John Grunsfeld will speak now.

John Grunsfeld: (remotely)

- I want to go through quick hallway discussion I had with Aki.
- Studies are to pick most compelling science and use studies to see what can be done. WFIRST not direct result of decadal survey.
- Science first! Figure out high priority science that can be done.
- "The science obviously has to be incredibly compelling"
- On hazard side: specifically in spectroscopy of small exoplanet atmospheres around nearby stars, it would be unfortunate if we have a proposal accepted and build it, and in the end, the best it call tell us is that there are interesting signatures, and we have to go build a bigger telescope to see what's there.
- If you have the bandwidth to look at large telescope parametrically going from something too small to too big, you can show how science scales across it. Science has to be compelling!
- Hard to predict what policy makers will decide. JWST was originally meant to be 4 m.
- Don't think about how little can you make it cost and then what capabilities will it have. Astronomers worry that if it's expensive it won't get started. I'm not concerned about that in decadal survey. I know Paul is, but we don't know what this telescope will cost.

- For instance, R=70 and looking at dozen rocky planets. That will leave us in situation where best case the answer is “wow this is great! Now we need a bigger telescope that might only amount to one more ring of segments.”
- Phase resolved spectroscopy will take a lot of light.
- In general you’ll find bigger is better, but study it to see how much better and if it’s worth it
- 80% of engineering and cost that goes into JWST goes in so that it survives launch.
- I agree we should do a start in 2020, not 2030
- We’ll be investing billions of dollars to send people around the moon. Let’s give them something to do. People in congress are excited about having them assemble this type of transformative telescope.
- Lee Feinberg has considered building telescopes about tessellations of segments. Robotically or human assembled in space. I know a little about working with telescopes in space! (laughter) These are things we know how to do.
- Pieces are better than “some kind of origami transformer concept” (laughter)
- Narrative important. Tell story about “amazing breadth and depth of science you can do with LUVOIR”
- If we go back and look at HST, it didn’t happen because people were asking “What’s the lowest cost telescope we can build?” We went in with 8 technologies that needed to be figured out.
- MSL, Cassini, “These were big dreams, and we made them happen. Yours is in the big dream category, but I think it’s an achievable goal.”
- “I want to help your team push its agenda”
- In 2020s there will be challenge for funding from Earth science. Only a really compelling vision for astro and astrophysics will result in strong program. Don’t be timid. We won’t have any UV-optical in space after 2030. “A vision as grand as LUVOIR is the future of US space astronomy”

Debra: We’d love to have you involved now that you’re retired!

John G: I’m meeting with attorneys to find out what I’m allowed to do. But science and tech are excluded from conflict of interest.

Karl: That’s right!

Julie: Your words are inspiring. I want to understand the political winds. I agree and want to endorse and going big. But facing decadal survey, they seem to be more and more prone to considering risks. Is it ok to rely on SLS?

John G: Very good question. We’ll know that within a year of transition before decadal starts. When I started 4.5 years ago, SLS and Orion very shaky. Now, SLS part of national policy and it would be extraordinary to kill it. Congress consistently has increased funding for SLS. We’d be foolish not to take advantage of it. Think about planetary decadal survey. It made three budget assumptions. One was worst case of flat + inflation. Middle is moderate increase in planet budget. Best case was large increase in planet budget. The actual budget passed was much lower than worst case. Here we are four years later and we’ve selected discoveries, about to do new frontiers, we have

Mars sample return, Europa mission, probably Europa lander. Because science cases are compelling.

Debra: Thanks so much for talking to us!

Avi Mandell (slideshow: Science Support Analysis Team)

- Assisting STDT with the efforts of evaluating LUVOIR architectures
- STDT sets goals, priorities; SSAT to understand implications in relation to different design trades
- Coordinates with STDT and external people
- Current people: Avi, Aki, Shawn, Geronimo Villlanueva, Jane Rigby, Stefanie Milan, Ravi
- E.g. yield calculations by Chris Stark
- SSAT wants to prioritize what the STDT wants

Aki: Tech notes I sent around were picked to highlight tech breakpoints. I just sent around one on launch vehicles. There's one on telescope temperatures, and one that still needs to be scrubbed for ITAR. Also short wavelength coatings for UV. Other four will be done very soon.

Avi: On Tech Notes, we can continue to evolve them and whip up additional Tech Notes.

Nick Cowan: What are the topics of Tech Notes?

Aki: Launch vehicles, long wavelength limit, stability, telescope temperature.

Mark M: How about astronaut assembly?

Aki: No. And UV coatings not written yet but on to do list. We have a draft on detectors, too.

Avi: Further ideas would be helpful. We have a lot of materials and we can provide a summary on thought from engineers.

Nick Cowan: I want a detector tech note.

Courtney: Does cold temperature include spectra or just cost? '

Aki: That's part of the stability?

Mark M: Is there a cold coronagraph, warm telescope?

Avi: Discussions about moving an instrument off. Coronagraph would be quite a challenge.

Shawn: There's a white paper on what you can do on a warm telescope but cold detectors.

Harley: There's a future issue of JAVIS relevant to you.

Norman: As far as paper on assembly in space, what do you want to get out of it Mark?

Mark: We were charged with thinking big. How do we do that?

Lee: I did a paper on a 20 m assembly. We can provide as white paper.

Aki: Does it need to be made intelligible to astronomers?

Lee: That paper is more comprehensible than the stability one.

Nick Cowan: How many person hours a week does this team have? What scale projects can we farm out?

Avi: I have internal GSFC funds. This isn't full time job. We pull together a team with broad expertise and can reach out to community. We could also do important but rapid turnaround tasks. And we can recruit a postdoc. But we all have other jobs.

Aki: Potentially we could do thesis-scale projects. We've done so in the past like Chris Stark's work. If it's a thesis scale project, chances are it'll be done by a postdoc. We are capable of coordinating that kind of work.

Nick: So my grad students could coordinate with you?

Avi: Yes!

Aki: Things that can turn into actual papers are really good. Smaller things are Tech Notes. We want to do ambitious things.

Debra: Let's set up leadership for science working groups. We have exo, COS, solar system, tech, and international. I can identify leaders of international. Antonella wondered who will be at SPIE meeting. Who can stay an extra day?

Aki, Brad, Debra record people with raised hands.

Kevin France: There are LUVOIR talks and STDTs session.

Debra: With international partners, we're hoping you'll organize your communities and solicit input. Nominal timeline is try to put something together before next face-to-face in August. Volunteers for SWGs? We'll send out an email to everybody. For tech?

Matt Bolcar: What are you asking for?

Debra: A specific leader to organize people in the community. We want four, plus international. Exoplanets, tech, cosmic origins, solar system.

John O'Meara: I volunteer for Cosmic Origins.

Aki: John can have overall oversight. Exoplanets? Mark Marley? Should we put Avi as a co-lead?

Shawn: Dave Redding volunteered to lead tech group.

Aki: I'd like to have Matt as co-lead to interface with the engineering team.

Debra: Solar system?

Britney: There's really only two of us.

Working Groups and Leads:
Exoplanets – Mark Marley, Avi Mandell (co)
Technology – Dave Redding, Matt Bolcar (co)
Cosmic Origins – John O'Meara, Jane Rigby (co)
Different sub-teams? Daniella Calzetti – galaxies, Illaria Pascucci – planet formation
Solar system – Walt Harris

Debra: This is a great start. Let's go to Gary who is calling in now.

Jason T.: Every mission a software development project. This cuts across all of the scientific categories.

Leonidas: Can we make these resources available centrally?

Aki: Yes, we're figuring it out.

Harley: I suggest a couple folks to lead in professional outreach. You are now talking to future members of decadal survey. Talking to them should be a priority.

Debra: Yeah.

Aki: Interesting point.

Debra: Each chair, identify somebody in your group for professional outreach.

Avi: Who wants to co-chair with Jason on Simulations?

Aki: I want to!

Simulations Working Group – Jason Tumlinson, Aki Roberge

Shawn: Now for Gary Blackwood's presentation.

Gary Blackwood (slideshow, remote, "Exoplanet standard definitions and evaluation team")

- In 2015, became obvious that HabEx and LUVOIR will consider overlapping science cases

- HQ asked for “common yardstick” → exoplanet standard definitions and evaluation team
- Slides on what this team is for
- Who is on it: Rhonda Morgan, Bruce Macintosh, Dimitri Savransky, Chris Stark, Avi Mandell, Ruslan Belikov, John Krist, others to be STDT liasons
- “apples to apples comparison”

Aki: New draft charter different from old. New feature is additional oversight by Alan Boss group. Why is that needed?

Gary: Fair comment. In past, APD has asked that ExoTAC provide independent assessment of products out of program office. I welcome another set of eyes. As example in AFTA coronagraph working group, we included step for Alan Boss to comment on process and product coming out of that team. In spirit of openness, we include that.

Mark Marley: Will this group set standards, e.g. albedos for planets in different bandpasses? In TPF-C albedo set for Earth was off by 50%.

Gary: Standards team about adopting not imposing standard. They will look at metrics STDT is using and do best to adopt common input assumptions and metrics. Those terms essential to apples to apples, but standards team won’t impose. Will adopt. Liasons to the two teams should work this out, especially low hanging fruit for common assumptions.

Vikki: What are you doing in the way of program modeling? Is that observing? Do you have instrument simulators? How much architecture is there in doing these simulations? Is this a table of input references? Or are you doing simulations to check yields for example?

Gary: It’s the latter. It’s a simulation check. This is an independent check of some, not all, metrics. Code that Chris Stark and others developed can be used. One example is we’re drawing on positive experience for astrophysics at time of WFIRST coronagraph. There were six different science teams developing telescope parameters; important to ground those models. Not all teams brought all the same assumptions to the table. Science teams should adopt common figures of merit and points to compare relative merits of these two studies.

Shawn: At ATLAST ExoPAG EC, SAG 17 planning to look at different starshade architectures and decide standard ways to compare those. Thought that ExoPAG should do one for coronagraphs. Suggested that there should be cross-talk between SAGs of starlight suppression mechanisms. Suggested that standards team could provide this role.

Gary: Just heard about that yesterday. There’s definitively some value there.

Debra: Thank you Gary. We’ll go on to Chris Stark’s presentation.

Chris Stark (slideshow on exoplanet yields)

- Max distance ~ 1AU/IWA
- Have to make assumptions about frequency of Earthlike planets, dust disk thicknesses, planet albedos, etc
- Yield code doesn't assume we know what stars the planets will be around. We can calculate probability of finding planet around star. (completeness parameter)
- What of fraction "exoEarth cloud" around a star is detectable? Yield = completeness * eta_earth

Mark Marley: This is with real Hipparcos catalog?

Chris: Yes

Vikki: What is crescent phase function?

Aki: Lambertian.

Chris: Most planets at quadrature or gibbeous. Lambertian pretty good in this regime.

Aki: Vikki does have a point. If you include real phase function it will make crescent planets brighter.

Chris: That will help a starshade mission.

Nick Cowan: It would be within the IWA.

Vikki: Anything past quadrature will have an increase.

- Altruistic yield allows for re-visits

Mark: Is this assuming you see a dot?

Shawn: This tells us we've collected the light from one.

Nick: You want to maximize number of Earths, not Earths relative to other things?

Chris: Yes, maximizing Earths.

Brad: You have to do this for each star, know its distance, mass of stars, so you know what range of orbital periods are in habitable zone? And that's where you get probability distribution?

Chris: Yes.

Aki: These are all Hipparcos stars within 20 pc.

Chris: Also depends on underlying distribution of what real exo-Earths is.

Courtney: Only Hipparcos in 20 pc? Or including faint red stars?

Chris: It's all the Hipparcos catalog.

Aki: When I say stars out to 20 pc, that's what gets chosen by the technique, not what gets put in.

- Method tells optimal observing time to look at a star, delay time between visits (for planet to move into visibility)

John O'Meara: Chris, how many stars around Starry McStarface? (laughter)

Illaria via Shawn: I'm assuming you've discarded systems with giant planets at 1 AU?

Chris: I do not concern myself with any planet not Earth-size and in HZ. With any telescope optimized to find Earths, you will get a vast array of other planets and spectra for free. Don't worry about finding other types of planets. Yield estimates adopt eta-Earth for just Earthsize planets.

Nick: You are ruling out binary stars?

Chris: Yes. Binaries closer than 10 arcsec.

Karl: That number could be revised.

Aki: I want to re-emphasize Chris' point. If you think you will increase yield by throwing out stars, you're thinking about it the wrong way. Yield will go down if you throw out stars.

Chris: You want to rule stars IN.

- Yield scales with D^1.9. If you want to double yield, increase aperture by 30-40% or increase lifetime of mission.
- Starshades fuel or time limited

Courtney: Do you experiment with multiple starshades?

Chris: No not yet. Stuffing two starshades in the rocket with the telescope reduces fuel mass you can launch at the same time so you don't gain double the yields since both starshades get fewer moves.

Laurant: 10 years ago, Olivier wrote paper of fundamental limits of performance of coronagraphs. Do you get theoretical best performance? How do your results compare to back of envelope calculation you showed?

Chris: I would not expect scaling relationship with aperture size will change. Every other scaling relationship can change where you are in parameter space. Scaling with D won't change because more collecting area, smaller IWA, smaller PSF so less noise mixed in.

Illaria (online): Has someone in RV community taken up the task to identify giant planets in the habitable zone of stars?

Debra: Yeah we have magnitude studies from two decades now. This gets through and beyond HZ. Good point to involve these surveys. I'm not sure we'd want to throw them out.

Aki: We probably DO want to observe them. We'll know we'll see a planet.

Shawn: Unless we exclude them and then we'll observe every kind of planet except HZ giants.

Debra: I don't think we'd exclude them.

Aki: If you know inclination in advance, yield should go up a lot. Precursor knowledge would be useful. If you can detect interplanetary dust in system, that should tell you where ecliptic plane is.

Karl: WFIRST may give you ecliptic plane for dust. In this mission, 1^{st} visit to star you'll see exozodi. You won't know exozodi level until you fly the mission.

Debra: You're still getting a dot, so having mass is a huge boost to productivity

Chris: If you have energy-resolving detector w/ low noise to get spectra during detection, you'll get spectra of some Earths for free during detection phase. This is an advantage of the coronagraph. The starshade, on other hand, you can devote follow up characterization to every observation without impacting yield.

Nick Cowan: Anyone know if Gaia will be useful for precursor info?

Karl Stapelfeldt: Yes, it can get Jovians.

Jason Kalirai (slideshow on General Astrophysics landscape in 2030s)

- What will astrophysics landscape look like after JWST and WFIRST?
- Also discusses LSST (high cadence wide field observations)
- WFIRST and LSST teams thinking about new legacy deep fields.
- GSMTs : high res, small fields
- European Extremely Large Telescope
- TMT will make 1^{st} discoveries soon
- One of the drivers of LUVOIR from NASA astrophysics 30 year roadmap is considering nearby galaxies and active accretion processes. Star formation histories of nearby galaxies.
- Next step in studying galaxy formation is to expand sample to see if differences we currently see in nearby galaxies is just stochastic
    - With LSST and WFIRST we will get much higher quality galaxy maps
- We understand luminosity function to galaxies to redshift of about 8, but it breaks down beyond that
- WFIRST deep field is bigger than HUDF and has 1 million galaxies at a time
- Resolving basic building blocks is "next big breakthrough"
- Vikki's "Planets are hard" diagram
    - Many things on the "planets are hard" diagram are astrophysical in nature

Olivier: Contrast ratio? (missed most of his question)

Leonard: In nearer future, ELTs can go to 4-5 microns where contrast is better

Jason: Similar even for Keck

Nick Cowan: Re. Chris Stark's yields, if these calculations are sensitive to other large planets that ELTs can detect, will we be able to constrain inclination?

Aki: Doesn't sound like time frames are commensurate. ELTs not ready until 2030s

Olivier: Adaptive optics: people looking at small modifications to existing instruments. Europeans will have adaptive optics and a coronagraph. Exciting results soon on massive and young planets. Habitable planets will take more time.

Avi: We've discussed need for IR capability for LUVOIR. Where will there be need for (unintelligible)?

Jason: JWST has mass margin problem, but resolved. JWST now in very healthy mass stage. Can top up fuel tanks more than before. Expectation is JWST will have 10 year life. Will be significant overlap between JWST and WFIRST. Beyond 1.2-2 um, given JWST optimizing for those wavelengths, hard for another telescope to complete with those. Baseline by assuming JWST has 10 year life, nominal is 5.

Nick Cowan: JWST great in IR. It can't do direct imaging of Earths around sunlike stars. I remember at some point some of us talked about a starshade for JWST. Is that still possible?

Karl: Project refuses to make fundamental modifications to telescope. Starshade has to be on sunward hemisphere of telescope (else reflecting sunlight) but JWST tilt can't tilt much into sunward hemisphere. Therefore, thin viewing range.

Nick: So, if we want observations of habitable terrestrial planets around sunlike stars it'll have to be on LUVOIR.

Karl: Or whatever comes after.

Aki: Can you wait another century?

Marc: Jason listening to your talk, one might conclude LUVOIR has great capabilities for general astrophysics but a 4m might not.

Jason: If you look at sensitivity of JWST vs everything we've had the gains we have are between 1-2 orders of magnitude. In that era of post-JWST science, it'll be incredibly difficult to compete with what JWST has done. WFIRST is 2.5 m telescope that is only competitive because of transformative instrumentation. It has a great coronagraph and FOV 100x bigger than any space based telescope. 4 m only competitive if has revolutionary instruments, but I have a hard time seeing this myself.

Karl: HabEx is discussing UV performance w/ new detectors. Also wide field optical imaging.

Aki: Wide field optical imaging? Shortward of WFIRST?

Karl: Yes, unexplored phase space.

Jason: I'm chair of working groups of filters on WFIRST. We are almost certainly going to have blue filter on WFIRST. We will have optical wide field imager.

Karl: Don't you get one optical filter?

Jason: We have a Z band filter. We will add a 500-700ish nm filter. Will have almost continuous coverage. Also have a dark filter slot for calibration. Trying to figure out if we can get darks with a different technique. If that opens up, we'll add another filter.

Karl: Only 1 filter wheel?

Jason: Yes.

Aki: So, if WFIRST does go shorter into optical, then would only difference between WFIRST and HabEx be 2.4m vs 4m diffraction limit?

Karl: (can't hear)

Jason: You'll have info on what filters are picked very soon.

Lee: WFIRST to be cooled?

Jason: We've studied that. Sensitivities better if we cool it.

Brad: What does that do to stability?

Lee: Their error budget is 150 picometers. Ours is 10. We need totally different raw contrast.

Debra: We still want to respond to O1 deliverable. We want to understand hard stops for technology. Tech group please produce digestible document. I will email everyone with assignments individually and also send emails to science working chairs to set up teams, set up figures, interact with community, simulation requests.

Jason Tumlinson (visualization codes he's developed)

- Turned Marc's excel spreadsheet into exposure time calculator. Saves you time deriving photometric limits.
- I will do this for spectroscopy limits. This one only uses a quasar. You can change redshift, make brighter, make fainter.

Avi: What is this code written in?

Jason: All python. Underlying python can be done independently. Bocet (spelling?) wrapper

Avi: Will these be a python live notebook?

Jason: This is a public website

- Widget to visualize exoplanet yield calculations
- Spatial resolution comparison
- VPL spectra: "build your own planet" spectrum
- Lesson from AURA report: don't make the mistake of NOT providing the outside community with opportunity for input and also tools they can use.

Kevin France: Please make user input spectrum!

Jason: I have to solve technical problem of uploading files. I didn't write a single line of python until last summer!

Vikki: How did you validate these codes?

Jason: Well, that varies by which you're talking about. We spent a long time on the resolution calculator, vetted against filters.

David S: But on that one there isn't noise.

Jason: Yeah. It corresponds to high signal to noise.

David S: That's something you could add.

Jason: Yeah.

Vikki: What about photometry?

Jason: There are a number of assumptions built in about diffraction limit, etc. I think I will have easy/advanced tabs for slider. Pretty standard exposure time calculation. Checked against Hubble.

Debra: Thank you so much! We have to move on.

Aki: Now going to go into splinter sessions. As prep to go back into that, let's take another crack at science document. I encourage you to think about first step. Focus on what headings should be in that document. Try to get broad, shallow big picture of science. As an aid, I whipped up three documents. I did an exoplanets case, a cosmic origins case, and one solar system.

For example, just write down high level science question we're trying to answer. E.g. "Are Earth-like habitable environments common or rare on worlds around other stars?" Word-smithing we can do later. I want to get the tone.

Next level, go a little deeper, not all the way down to bottom. Science measurements: what is it we want to measure? Find planets in HZs of nearby stars, measure water vapor in atmospheres, measure orbits to determine surface energy input, measure surface atmospheric pressure.

Then we drop down another level and talk about observations. To get those measurements, what observations must you do? Describe the observations. E.g. Direct imaging search, optical/IR spectroscopy, multi-epoch imaging, near-IR spectra, planet mass determination.

(she also shows a COS one)

Debra: This is good format for homework.

Brad: Yes this is good for homework. From breakout sessions, I want to see broad science topics and capabilities we need to address them.

Aki: No numbers, but by doing this exercise, just the act of forcing myself to think of observations, just writing the section headings made it clear to me what instruments you'd need. I don't know detail, but I see, for instance, there are two instruments here (regarding her cosmic origins example).

Even if you just fill out title, that will help us understand whose homework that is.

(splinter sessions end the meeting)

List of concepts/instruments people brought up:

- Use of SLS
- Serviceable mission
  - Serviceability through private sector
- Mirror sizes in between HabEx and LUVOIR ("interpolateable" sizes)
- Working with industry
- Modular design (helps with servicing ability)
- Vacuum tank testing (testing separate components)
- Tracking processes over time in solar system (Britney → she strongly emphasized tracking things over time; "change detection")
- IFU, multi-object spectrograph that works in UV (Mark Postman wants to track UV emitting gas)
- UV capability (to study ISM, gas, ionization; Mark Postman put heavy emphasis on UV)

- Coating mirror segments with different things (for UV capability)
- "Broad wavelength range" (Vikki discussion of O false positives)
- Detector sensitivity at 1 um needed! CCD and InGasAs die at 1 um
- Broad wavelength coronagraphic nulling (cut down integration time)
- Ability to bin down resolution to access more distant targets is reasonable time
- Broadest range possible
- Diffraction limited resolution for in-close (solar system) objects
- Integral field capability (solar system → Britney)
- 100 km resolution at distance of Pluto
- cooling the telescope
- deformable mirrors
- use of a starshade
- RV and/or astrometry capability
- Different types of mirror coatings (discussion of getting to shorter wavlengths than 1100 A)
- Neutral density filters
- Diachroics
- People want to be able to do parallel observations
- Sunshield preferred over light baffle
- Tools/simulators
- Involving other community members, professional outreach

Major themes I heard repeated:
UV capabilities, serviceability, what is our wavelength range?, relationship to HabEx, whether to cool the telescope, what to do with SLS