The Star Formation Camera - Descope Options

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This document outlines considerations that have been made to define descope tracks to reduce the cost associated with the *SFC* instrument, but also to assess the capability and scientific impact of such moves so that NASA can make an educated decision about whether such steps are well-advised or not.

As a starting point it is instructive to remind ourselves of the current baseline design for *SFC*:

Current Numbers for *SFC* From the Team-X study of the Camera design and associated technologies, the following estimates have been made:	
Parameter	Current Value
Overall cost (50% number):	$400M
Mass:	453 Kg (system) 65 Kg (electronics) 53 Kg (optics) 199 Kg (structure) 103 Kg (detector)
Power:	435 W

Reduction from 2 Channels to 1

An obvious descope option is to reduce the overall size and data load requirements of the instrument by removing the second observing channel and moving to a single channel model that images the field with a single array of detectors, through a single filter wheel assembly, built of chips that have been optimized for the full Si-passband from 190-1075nm.

Cons:

- Such a move would result in a **huge reduction** in observing efficiency, the **largest of any one** descope under consideration – we would be **unable** to complete our core science in the earmarked 1.25 yrs per instrument
- All of our core science surveys (all Tiers) would **cease** to be "systematic" or "comprehensive”
- This would reduce the *Theia/SFC* to another *Hubble* whose legacy after 10 years and $4-5G investment would be a litany of people's favorite objects
- This one channel instrument would require a re-optimization of the optical design to use a variety of new component pieces – such as a **huge filterwheel** assembly to accommodate all the science-driven filters necessary to complete the core science program
- Since we would be unable to observe both the blue and red parts of the passband in parallel, much longer dwell times on each target would be required to get all the filters we’d need to the depths necessary to achieve the science

Pros:

- Cost Savings of ~$115M
- Mass Savings of ~100 Kg
- Power Savings of ~200 W
- Removed need for dichroic
- Smaller number of CCDs to fabricate and test to flight readiness level
- Reduction of necessary size of radiator and heat pipes – although this is now a far smaller concern than earlier estimates had stated, because of the very low power now estimated for each chip, based on the revised modular electronic design

Reducing the Effective FoV

Two of the primary properties of the *SFC* are the wide field of view and the high resolution per pixel we have designed it to support. The unique phase space this provides access to results from the **combination** of these two qualities to locate and characterize large numbers of heretofor unknown targets spread across large areas of sky, whose location and optical characteristics are unknown but once discovered whose nature requires the high resolution of an *SFC* pixel (18 mas) to finish the analysis. Another logical descope to consider is the simple reduction of the size of this field of view since it drives the number of detectors needed, the power required, the thermal control of the system and the data load that needs to be stored and downlinked.

Cons:

- If the reduction of the FOV is <~30%, *SFC* could still be fairly comprehensive, but…
  - we would **lose the overview** of the star formation process on larger spatial scales and would have to limit our total survey area reducing the total number of Galactic targets by more than 50%
  - In the Magellanic Clouds: likely only one half of target fields would be possible plus some sparse sampling of interesting pointings in the other half
  - In Nearby Galaxies beyond the Local Group: the number of targets and pointings would stay the same, but we would lose the sampling of satellite systems and surroundings, at least for the nearer ones
  - Cosmological survey: **direct hit in cost to sample 10 deg^2** - this is difficult to mitigate if the goal is to find objects with a surface density of <1 per deg^2.
- If the reduction is more than 30% then…
  - *Theia/SFC* becomes a *Hubble* like mission. The **core science and systematic, comprehensive surveys will be lost** - unless we can rely on the community to chip in to make up for the additional time needed (e.g. for *Theia/SFC* hyperdeep+wide fields - not entirely unlikely, but *HST* was 6 years into its mission before the original HDF-N and –S happened and more than a decade before the HUDF, GOODS, COSMOS, Carina, etc.. became viable)
  - For surveys other than single deep and/or wide fields, **the situation is even worse**: surveys like ANGST and Virgo Cluster Survey took >15 years before being granted time on *HST*, and the former had to cope with the camera (*ACS*) actually dying halfway through and is now limping along with *WFPC2*

Pros:

- Reduction of 50% to half the FoV:
    - Cost Savings of ~$100M
    - Mass Savings of ~120 Kg
    - Power Savings of ~200 W
- Reduction of 75% to one quarter of FoV:
    - Cost Savings of ~$190M
    - Mass Savings of ~160 Kg
    - Power Savings of ~300 W
- Smaller number of CCDs to fabricate and test to flight readiness level
- Reduction of necessary size of radiator and heat pipes

Relaxing the Diffraction Limit Spec to 500nm on the Primary

The diffraction limit specification on the primary mirror for *Theia* is primarily driven by the imaging needs of the *SFC* in the very bluest part of its passband. There are also requirements driven by the UV camera on *XPC* that is used for terrestrial planet characterization, but the *SFC* is the driving force behind this requirement. While initially viewed a huge cost driver it has become apparent from discussions with ITT that the **only reason** a 300nm accurate mirror has not been milled to date is because "**noone has asked for one**". When the milling is being performed on a monolithic mirror, it is a simple matter to continue to polish until the higher spec is reached rather than stopping when a lower number is met. The cost associated with such a decision is deemed minimal and should not be seen to be a driver. The risk associated with the additional polishing is also not seen as a risk by the vendors.

Cons:

- In our opinion this **defeats the whole purpose** of moving to a new orbiting Observatory – an increase in aperture alone is not enough.
- We have to open up **new** regimes in parameter space and sticking with *HST*-like performance will **not** give us the edge over missions in other wavelength regimes.
- While our enlarged areal coverage is one good selling point, it alone would likely not be a winner if we have to convince a very large portion of the astronomical community that we are the horse to bet on in terms of selecting a Flagship project.
- We have to offer more:
    - the ability to resolve stars in external galaxies out to interesting distances (we may reach all the way to where the Hubble flow starts to dominate over local density effects for methods like Brightest Star distances and even TRGB distances)
    - Offer better resolution for cosmological work where the average size of galactic and sub-galactic systems is a strong function of redshift - right now, the majority of the faint objects found in the HUDF have apparent effective radii that bunch up against *HST's* diffraction limit, signifying we cannot determine their structure - to do so, we need to have significantly higher angular resolution than *HST* or we won't learn much new on the evolution of galaxy structure
    - for Galactic and Magellanic Cloud work: who knows what the actual upper mass limit of stars is? Are all of the highest mass stars found in binary or multiple-star systems? Can we understand the integrated emission from a

nebula without resolving the detailed structure around shock fronts.

- **Lost science**:
  - Resolving the full stellar populations in our and other nearby galaxies – the blue end would be lost
  - Loss of resolution in the blue/NUV for diagnostic lines such as MgII and [O II] for analysis of circumstellar disks, jets and shocks
  - Loss of resolution in the blue/NUV to understand the microphysics of gas and interfaces in HII regions and SNRs
  - Loss of stellar population sample in the blue for the Magellanic Clouds which will affect the clustering analysis for the faint blue populations
  - Intimately affect the HuGS resolved stellar population analysis and undermine our intent to use CM and CC diagram fitting to generate spatially resolved SF histories
  - Similarly affect and compromise the larger less-deep survey under LoVeSoNG and curtail the parameter space intended to be explored by the 500-galaxy sample

Pros:

- Cost Savings of ~$??M (specific numbers unavailable from ITT at this time)
- Potential cost savings in FPA since the Rayleigh criterion will now be different and the total number of CCDs needed to pave the field required would be less

Removing the LiF Coating Requirement for the Secondary

The overall science program for the *SFC* is rooted in the originally proposed science program from the *Star Formation Observatory* – the uv/optical camera from which evolved into the blueprint for the *SFC* as presented in this report. That original proposal contained substantial complementary FUV science that defined the specifications for a high resolution (R~40,000) FUV (λ = 100-170nm) spectrograph using the latest MCP detector technology. We are happy to report that the current working design for *UVS* meets all of our original specifications and allows our original FUV science to be completed. In fact that science has been adopted by the *UVS* team as additional "crossover" science to augment their original IGM-related science program. However, to achieve a high throughput with this instrument, it became necessary to require that the secondary on the *Theia* Observatory was coated in LiF to increase the FUV reflectivity. The size of this optic (49cm diameter) is well within the heritage provided by the coating and flight of the *FUSE* optics, whereas any such proposal to coat the 4m primary was deemed to be too risky to be considered – that optic will be coated with MgF_2. The hygroscopic nature of LiF does add risk to the mission, and cost to the hardware handling and contamintion control during assembly, I&T, transport and launch. Removing this requirement would simplify the problem but **essentially render useless the *UVS* instrument** and a large part of the *SFC* science program, as currently conceived.

Cons:

- We would **lose 90% of our FUV science program** in Tiers 1-3
- Terrible for calibration and interpretation of the data from our imaging surveys, for the physics that we would hope would result from the Galactic, Magellanic Clouds, and IGM surveys.
- We would be **unable to determine the detailed energetics of star forming regions**,

starting from the energy blasted into the surrounding ISM by young massive stars, and perhaps even the kinematics of some regions.

- We would probably not learn enough from just the 190-1075nm spectral energy distributions alone to assess evolutionary states, dependence on metallicity, etc.
- We would **lose the ability to learn how gas from the IGM winds up into galaxies**, the details of the physics of the interface layer, the detection of possible reservoirs of gravitationally bound metal-enriched gas at relatively large distances from galaxies, and for very small systems the study of unbound galactic outflows back into the IGM.
- Since it would almost certainly **cause the UVS team to leave the project** it would seriously hurt the viability of the overall Theia concept.

Pros:

- Cost Savings of ~$10M in fabrication of Observatory
- Cost Savings in contamination control of Observatory between I&T and launch (~$10M)

Reduction of the Observatory Primary Aperture

While low on the list, the largest single line item on the manifest for *Theia* is the size of the primary mirror. Estimations of this cost vary substantially, but because of the relative share of the mission cost, the size of this optic bears consideration. It was an original driver from the *XPC* proposal that 4m was the smallest aperture that could be seriously considered for the problem of imaging exoplanets using the external occulter method. The resolution afforded by this aperture is central and critical to the limiting resolution necessary for the *SFC* science program as presented. While entertaining to consider, the primary optic is the heart of the overall mission and reducing the aperture size should be **the very last consideration**.

Cons:

- If Reduction is to 3.5m:
  - Loss of angular resolution is relatively small – the Rayleigh criterion becomes 21 mas @ 300nm
  - Loss of collecting area is 24% - this **would seriously diminish** what we could do cosmologically and make it much harder to find the very faintest objects at high redshift
- If Reduction is to 3m:
  - Rayleigh criterion is now 24 mas at 300nm and we begin to lose our access to blue stellar populations in nearby galaxies, our ability to resolve structure in nearby HII regions, protostellar systems, and our definition at high redshifts
  - The loss in collecting area is now 44% and in some cases **renders large parts of our science program impossible** in the core mission lifetime identified, in others impossible at all

Pros:

- Reduction from 4m to 3.5m:
  - Cost Savings of ~$300M
- Reduction from 4m to 3m:
  - Cost Savings of ~$630M

Adding a NIR Imaging Camera

This is not simply a list of "things to cut". To fulfill the spirit of presenting options to NASA that are driven by the issue of trading cost with capability, we felt it was wise and justified to present one option that goes the other way – an addition to the baseline *Theia/SFC* design that adds a considerable new capability at a relatively modest investment. A more detailed account of this option is included as another appendix to this final report to NASA, but we include here some of the broader conclusions for the reader to compare to what has gone before, above. We propose the **addition of a NIR camera** modeled in some characteristics on the capabilities of the uv/optical *SFC* channels, but focused on the valuable additional science that would be possible with a camera that could image at 63mas resolution the same field of view offered by the *Theia* primary and used by the *SFC*, but **across 0.9 to 1.9 microns, through two channels using a dichroic positioned at the blue end of the H band**. Such an instrument would be **quite complementary to both the *JWST* and *JDEM*** missions in terms of field coverage, filterset suites and high resolution and would provide parameter space coverage for a series of cosmological questions that neither mission can address as currently proposed or in development.

Pros:

- Extends wavelength coverage of the imaging capability of *Theia* into the hole potentially left by *JWST* between 1 and 1.9 microns
- Allows access to objects in the cosmological vital regime between redshifts 6 and 13 – the era marking the peak of reionization when the formation of the very first galaxies occurs
- Should be presented to the Decadal Survey and the community as an option
- Is being presented to NASA as an interesting and technically feasible option that would allow additional science to be done with Theia for a marginal (~$100M / ~$5G = 2%) additional cost (for the single channel version; 4% for the dual-channel version).
- In particular, the exciting redshift regime in the next decade or two will be centered around z ~ 11 (*WMAP* year-5 result), which is the height of the reionization era, when dark-matter halos grew to the point that clumps of Pop III → II stars condensed in the first proto-galaxies.
- That redshift regime is inaccessible to us without a near-IR camera that can access wavelengths up to ~1.95 micron.
- Its cost should not be included in the price for the baseline *Theia* and/or *SFC*. This is an added extra, an upgrade.
- The design itself is relatively flexible thanks to highly reflective Ag-coated fold mirrors

Cons:

- Additional Cost of $100 (single channel) / $200M (dual channel option)
- Additional Mass of ~300 Kg
- Additional Power of ~200 W
- Possible packaging problems, in the case of the dual-channel option