U.S. Participation in the JAXA-led SPICA Mission: The Background-Limited Infrared-Submillimeter Spectrograph (BLISS)

Technical and Cost Report for the Astro 2010 Decadal Survey*

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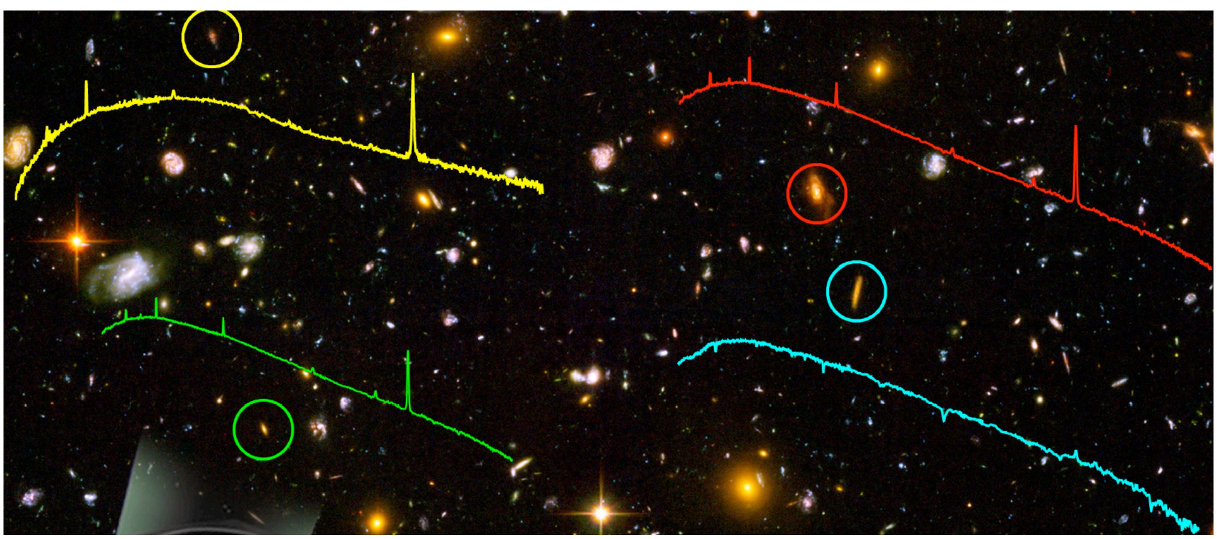

Hubble Ultra Deep Field with ISO Long Wavelength Spectrometer (LWS) spectra of nearby galaxies (Fischer et al., 1999). The spectra extend from 48 to 200 microns, a subset of the BLISS wavelength range for redshifts 0 to 3 (at higher redshifts, the longest wavelengths will be shifted into the ground-based submillimeter windows.) BLISS on SPICA will readily obtain spectra similiar to these but at higher spectral resolution galaxies and redshifted to as far as z$\sim$5. The circles show the BLISS-SPICA beamsize at 180 μm.

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Contents

1 Executive Summary

We outline a plan for US participation in the Japanese-led Space Infrared Telescope for Cosmology and Astrophysics (SPICA) mission currently under development with launch envisioned in 2017. SPICA features a 3.5-meter telescope actively cooled to below 6 K, operated at L2 with a 5-year lifetime. It will be the world's best and only space far-IR platform at the end of the coming decade. The large cold aperture offers the potential for mid-IR to submm observations which are limited only by the zodiacal dust emission and other natural backgrounds. If equipped with suitable instrumentation, SPICA can enable sensitivities comparable to JWST and ALMA but in the crucial and still relatively unexplored far-IR spectral range which carries half the photon energy ever produced in galaxies.

We have been working with the SPICA principals in a study of a sensitive US-built spectrometer BLISS which would be one of the main science instruments. The collaboration is compelling because US detectors for far-IR / submm wavelengths are world-leading, and our provision of BLISS has the potential to dramatically enhance the scientific return of SPICA. BLISS is envisioned to cover the $\lambda \sim 38$–$430\,\mu$m band with grating spectrometer modules using sensitive superconducting bolometers, and BLISS / SPICA will be 4–6 orders of magnitude faster than currently-planned facilities for broadband spectroscopic observations of distant galaxies. An instrumental contribution to SPICA would also allow US scientific access to all the capabilities of SPICA, a great-observatories-class facility, at a cost well below a comparable US-led mission.

Participation in SPICA with an instrument such as BLISS is the top priority of the US far-IR astrophysics community for the coming decade.[†] In addition to the scientific value, SPICA participation also provides a platform for advancing low-background far-IR focal-plane technologies, the key technical hurdle for our community's long-term plans: US-led cryogenic far-IR missions CALISTO/SAFIR and SPIRIT.

We face a limited window in which the US can join the mission. SPICA has entered a"pre-project phase", corresponding to a NASA Phase-A study in Japan; and ESA's Cosmic Visions program is funding a consortium of European scientists in a study of the SPICA telescope and an instrument. While the SPICA partners are interested in the U.S. far-IR capabilities, they will now proceed with or without US involvement, and instrument resource allocations (volume, mass, power) are currently being established. NASA has recently (July 2009) released an AO for SPICA participation concept studies[‡] to enable US scientists to define interfaces and resource allocations in advance of a potential commitment pending a positive recommendation from Astro2010.

Per instructions from Astro2010, we present the approach and cost only for the proposed US hardware role in SPICA: the BLISS instrument and instrument-team science. The full mission implementation and cost will be borne by JAXA and ESA and is not presented.

The cost (with margin) to NASA for an instrumental contribution to SPICA, from inception through instrument delivery, mission operations, data archiving and instrument-team science is estimated at \$148M (\$FY09, reserves included). This includes a 24–30 month technology maturation phase beginning in FY11 to enable the highest-performance instrument. In return for this investment, it is expected that the US scientific community would obtain access to all of SPICA's instruments in partner open time, as with ESA's Herschel. Support for this Phase E US community activity is not costed in detail here, as most of it will fall in the next decade, but it should be comparable to the US observing program with Herschel.

[†] see `http://www.ipac.caltech.edu/DecadalSurvey/farir.html`
[‡] see `http://www.submm.caltech.edu/BLISS/`

2 Science Overview: SPICA is an Unparalleled Opportunity in the Far-IR

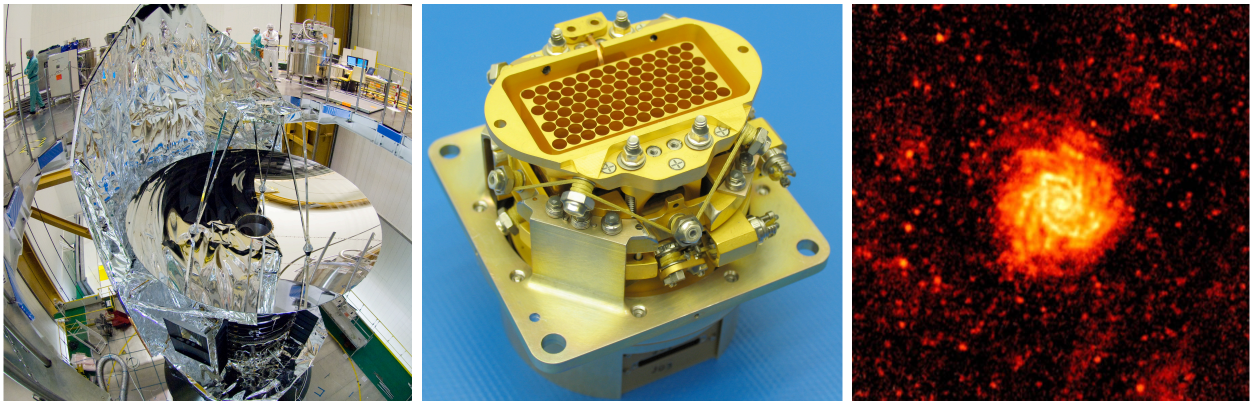


Figure 1: SPICA/BLISS builds upon the scientific and technical legacy of Herschel. (Left) Herschel is a 3.5 m telescope passivly-cooled to ∼80 K for far-infrared imaging and spectroscopy. (Center) Operating detector arrays developed at JPL for the SPIRE instrument, designed for mapping large areas of sky (tens of square degrees) to the photometric confusion limit. (Right) First-light image of M74 obtained with SPIRE at 250 μm. In addition to the central galaxy, numerous far-infrared galaxies are apparent in this short observation, many detected in 3 bands simultaneously. These far-IR galaxies are likely at high redshift, and SPICA/BLISS will conduct spectral surveys of a subset of the 10,000s–100,000s of sources expected to be detected and cataloged by Herschel. With its 3.5 m actively-cooled 6 K telescope and optimized spectrograph, BLISS on SPICA can obtain spectra of these galaxies at a rate 10^4 to 10^6 times faster than PACS and SPIRE spectrometers on Herschel.

The far-IR spectral regime is the repository of half the electromagnetic energy released in the history of stars and galaxies, and offers the only opportunity to probe the details of embedded star and planet formation and the processes in dust-obscured galaxies. Yet the far-IR has remained a relatively unexplored frontier compared with other wavebands because sensitive far-IR measurements require a combination that has yet to be fully realized: a large cryogenic telescope above the atmosphere and sensitive far-IR focal-plane technologies. The multinational SPICA team is now poised to provide build on the experience with IRAS, ISO, Spitzer, Akari, and Herschel to provide this capability. The most important attribute of SPICA is its sub-6 K temperature. *To understand this advantage, consider that at* $\lambda = 100\,\mu\mathrm{m}$*, even a well-designed passively-cooled* $T \sim 80\,\mathrm{K}$ *telescope such as Herschel is more than 10,000 times brighter than the natural astrophysical background due to solar-system and Galactic dust. Cooling the telescope to below 6 K virtually eliminates its emission relative to this background.* The sensitivity improvement afforded by a cold telescope can be dramatic, as resoundingly demonstrated with Spitzer's successes in the mid- and far-infrared with only an 85-cm aperture. SPICA is conceived in this same philosophy, and JAXA has invested significantly over the past decade to develop and verify closed-cycle 4-K and 2- K cryocoolers to enable a cryogen-free 5-year mission.

2.1 Open-Time Science with SPICA

SPICA's large, cold aperture offers potential for great-observatory-class performance, and, while the details of the observing allocation for SPICA are still being negotiated, it is antici-

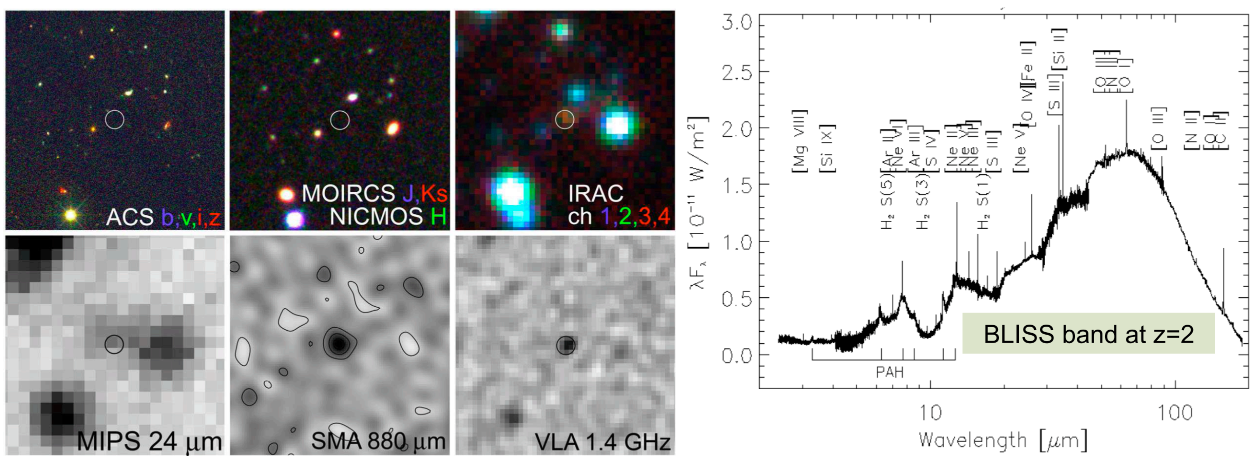


Figure 2: LEFT: Multiwavelength images (24″ on a side) toward a submillimeter-bright galaxy discovered with Scuba/JCMT in the GOODS-N field and confirmed using the SMA submillimeter interferometer (center bottom) which provides an accurate position [8]. The object is undetected in deep HST/ACS, HST/NICMOS, and Subaru/MOIRCS images, and is very faint in the Spitzer IRAC, Spitzer MIPS-24 μm, and VLA images. The redshift is unknown but thought to be $z \sim 4-6$. RIGHT: The complete mid- to far-IR spectrum of the Circinus galaxy from the spectrometers on ISO. The source is a nearby analogue of the high-z dusty LIRGs and ULIRGs. The spectral lines probe the contents and energy sources deep within the dusty core. BLISS on SPICA will for the first time obtain spectra such as these on galaxies throughout their history.

pated that U.S. scientists will have access to SPICA open time in exchange for the provision of BLISS (see responses to Astro2010 PPP questions*). The open time will likely solicit proposals for large legacy as well as general observer programs as has proven successful on the U.S. great observatories and is being implemented with Herschel.

The Japanese and European teams are studying powerful focal-plane instrumentation to optimize SPICA's scientific output. Mid-IR camera and spectrograph modules will complement JWST MIRI by extending the wavelength coverage to 37 μm, enabling wide-field surveys, and providing R $\sim 30,000$ spectroscopy. A mid-IR coronagraph will take advantage of the clean point-spread function provided by the monolithic telescope. A far-IR imaging Fourier-transform spectrometer (SAFARI) proposed by the Europeans is versatile imaging instrument and a variable-resolution spectrometer. The BLISS grating spectrometer we propose here offers the ultimate sensitivity for wideband extragalactic survey spectroscopy. SPICA is thus broadly poised to address pressing scientific concerns such as: 1) Charting in detail the birth and evolution of stars and planetary systems in our own Galaxy, 2) Discovering when and how the stellar populations and black holes in galaxies came to be, and 3) Probing the rise of chemical elements in the Universe, including those of life. We focus here on issues 2) and 3) above, which are related to the evolution of galaxies and their contents, and are particularly addressed with the BLISS spectrometer.

2.2 Dusty Galaxy Populations

Nearly 2 decades after IRAS's discovery of luminous and ultraluminous infrared galaxies (LIRGs and ULIRGs) in the Local Universe, the first submillimeter imaging from the ground has revealed a cosmologically-significant class of galaxies which have similar properties. Like

http://www.submm.caltech.edu/BLISS/decadal/BLISS_answers_final.pdf the LIRGs and ULIRGs, these sources are powerful, but are so dusty that they emit up to 99% of their energy in the mid-IR through submillimeter. A compelling recent example is the imaging surveys at 250-, 350- and 500-μmwith the Balloon-borne Large Aperture Submillimeter Telescope (BLAST) [9], a predecessor to the Herschel SPIRE instrument. BLAST finds that all of the far-infrared background light at these wavelengths indeed comes from individual galaxies. Moreover, 70% of the background light comes from galaxies at z$\geq$1.2, corresponding to the first 5 billion years of the Universe. More capable far-IR / submm imaging instruments are now being deployed (e.g. SCUBA-2, SPT, LMT, Herschel SPIRE (see Figure 2), CCAT), and it is expected that deep surveys will reveal thousands to tens to hundreds of thousands of dusty galaxies from the first half of the Universe's history. As these dusty galaxies are rapidly discovered, it becomes increasingly pressing to understand their true nature and context in the Universe: What was the role of these dusty sources in the buildup of stellar mass, the growth of black-hole, and the rise of heavy elements?

2.3 Spectroscopy with BLISS on SPICA

These questions are difficult to answer. The far-IR continuum alone provides little diagnostic or redshift information. Optical and even near-IR counterparts for these "submm galaxies" are absent or difficult to find (see Figure 2). Even where optical / near-IR counterparts exist, the measurements only probe a thin surface, and provide little information about the true underlying energy source. ALMA will be very powerful for detailed studies of spatial morphologies and kinematics, but it requires an a priori redshift, and measures only a single spectral transition at a time. *Sensitive wideband spectroscopy of the rest-frame mid- to far-IR with BLISS / SPICA will be the key to studying these galaxies as they form and evolve. It will both provide unambiguous redshifts and probe the astrophysical processes deep within the obscured cores.* More details can be found in our initial submission to Astro2010;§ the primary science objectives are presented in Table 2.4 and illustrated in Figures 3 and 4.

2.4 Responses to Questions

1. **Describe the measurements required to fulfill the scientific objectives expected to be achieved by your activity.** The science objectives in Table 2.4 all require wideband follow-up spectroscopy: observing galaxies identified in imaging campaigns with known position on the sky but unknown redshifts. The measurement must thus provide very wide spectral bandpass to observe multiple lines and allow for unknown redshifts. Sensitivity is also paramount. As Figure 4 shows, measurement of far-IR spectral lines in galaxies at redshifts of 5 requires detecting features with fluxes as low as $10^{-20}\,\mathrm{W\,m^{-2}}$.

2. **Describe the technical implementation you have selected, and how it performs the required measurements.** The only way to reach the required sensitivities is with a 3-meter class cryogenic telescope and a dispersive spectrometer (not a Fourier-Transform spectrometer) operating near the fundamental limit of photon noise from

*South Pole Telescope, Large Millimeter-wave Telescope, Cornell-Caltech Atacama Telescope
§available at `http://www.submm.caltech.edu/BLISS/decadal/BLISS_decadal_final.pdf`

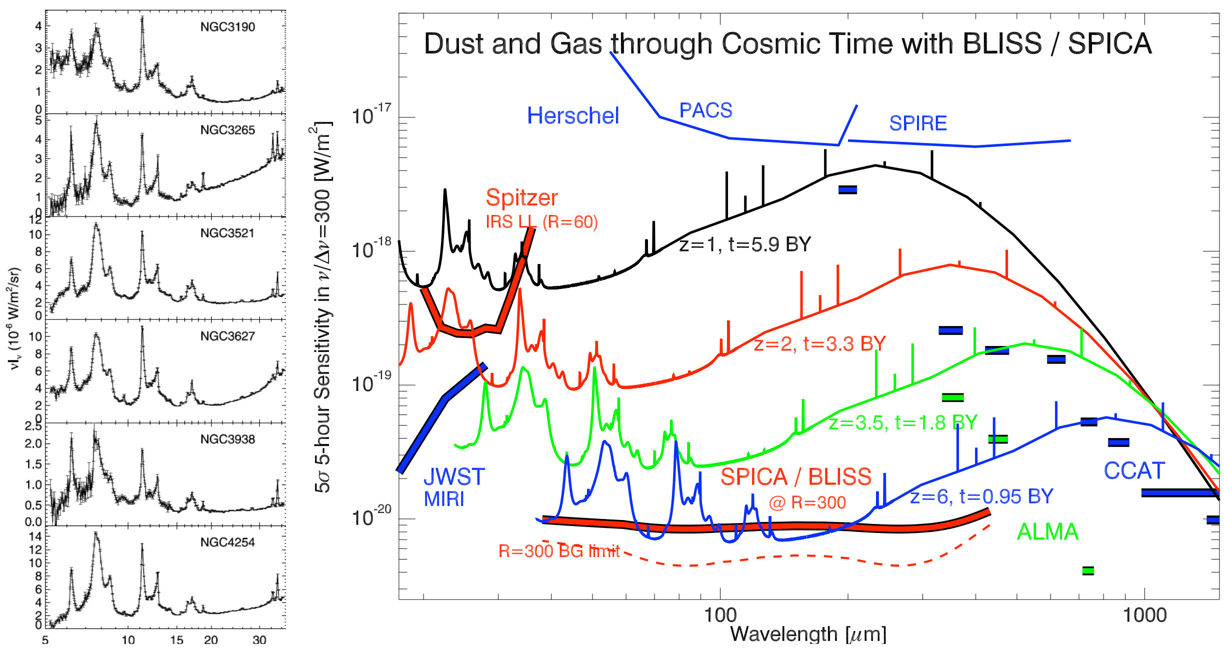


Figure 3: LEFT: Spitzer SINGS mid-IR spectra of nearby galaxies showing the powerful emission features from polycylic aromatic hydrocarbons (PAHs) [13]. RIGHT: the BLISS / SPICA sensitivity and redshifted galaxy spectra using the local-universe template and assuming $L = 10^{12}$ L$_\odot$. The mid-IR PAH features and the bright fine-structure lines are accessible for galaxies as early as 1 GY after the Big Bang.

the Zodiacal and Galactic dust emission. The telescope optics must be cooled to a few degrees K or its own emission will dominate the noise budget. To approach the fundamental background sensitivity limitations for an R∼700 spectrometer, the detectors must have a sensitivity measured in units of noise equivalent power (NEP) of 10^{-19} W Hz$^{-1/2}$ or better. Among dispersive spectrometers, the diffraction grating is the only way to couple a large instantaneous bandwidth. BLISS uses a suite of grating spectrometers illuminated with dichroics and polarizing splitters to cover the full 38–430 μm range. In order to achieve the required sensitivities, the 4224 detectors will be transition-edge superconducting bolometers cooled to around 50 mK and read out with a cryogenic multiplexer. Further detail on the BLISS implementation is provided in Section 3.1. We emphasize that the excellent point-source sensitivity of BLISS is complementary with the 2-D survey capability of SAFARI, which will find interesting objects for detailed study with BLISS.

3. **Of the required measurements, which is the most demanding? Why?** The most demanding measurement is spectroscopy of the very-high-redshift (z>5) objects. This requires the highest sensitivity and stability for long integrations, as well as the wide bandwidth.

4. **Performance requirements.** See Table 2.4.

5. **Flow down of science goals.** See Table 2.4.

6. **For each performance requirement, present the sensitivity of your science goals to achieving the requirement.** The science goals comprise a very broad

program, and the reduction in science return with performance is graceful. The history of galaxies is written at all distances and luminosity classes, and ample science return is assured with even the minimum instrument configuration for BLISS.

- A degraded detector sensitivity (larger sensitivity number) results in a proportional change the astronomical line flux sensitivity. For a given measurement, the observing time scales as the square of the sensitivity.
- A reduction in the total instantaneous bandwidth results in lost spectral information. This can introduce ambiguity in the determination of redshifts, and decreases the overall astrophysical diagnostic capability.
- A reduction in the spectral resolution $\lambda/\delta\lambda$ can introduce line confusion, since BLISS / SPICA will be so sensitive that multiple sources along the line of sight may contribute to the observed spectrum in deep integrations.

Table 1: BLISS Science Objectives and Measurement Requirements

Science Objective	Measurement Technique	Performance Requirements
Chart the history of metal production in dust-obscured star formation since the Universe was 1/10 its present age	[NeII] 13 μm, [SiII] 35 μm and/or [CII] 158 μm fine-structure (FS) transitions probe total star formation activity. [OIII] 53 and 88 μm FS line pair reveals massive star content. Aggregate spectrum provides unambiguous redshift for each galaxy. Measure out to redshift 5 in ULIRG-class galaxies.	- Sensitivity to spectral lines: $\leq 10^{-20}$ W m^{-2} in 4 hours. - Wide instantaneous bandwidth: 40–400 μm. - Resolving power >300 to avoid line confusion. $\Rightarrow$ Use wideband grating spectrometer on 3.5-m, actively-cooled telescope. $\Rightarrow$ Detector sensitivity: $\leq 10^{-19}$ W Hz$^{-1/2}$.
Study the interaction of massive black holes with their host galaxies when activity peaked at 1/3 to 1/2 the age of the Universe.	Measure [NeV] 14 & 24 μm and [OIV] 26 μm FS lines from the AGN coronal regions, and the [OI] 63 μm transition from X-ray irradiated host galaxy material in ULIRG-class buried AGN at redshifts 1–3. Aggregate spectrum provides redshift for each galaxy.	Same as above.
Investigate cooling in primordial gas filaments and condensations	Measure molecular hydrogen (H_2) rotational transitions at 28, 17, 12, 9.8 μm in lensed regions at redshifts of 3–6. Spectrum provides unambiguous redshift.	Same as above, wavelength coverage only needed to 200 μm.
Find and characterize the earliest dusty systems through their PAH features, the most powerful spectral features at any wavelength	Measure the broad features with $\lambda_{\rm rest}$=7.7, 11.3, 12.7, 17 μm at redshifts of 6–10, possibly in lensed systems (See Figure 3). Spectrum provides unambiguous redshift	Same as above, wavelength coverage only to 200 μm, resolving power only >100.

3 Technical Implementation: SPICA and BLISS

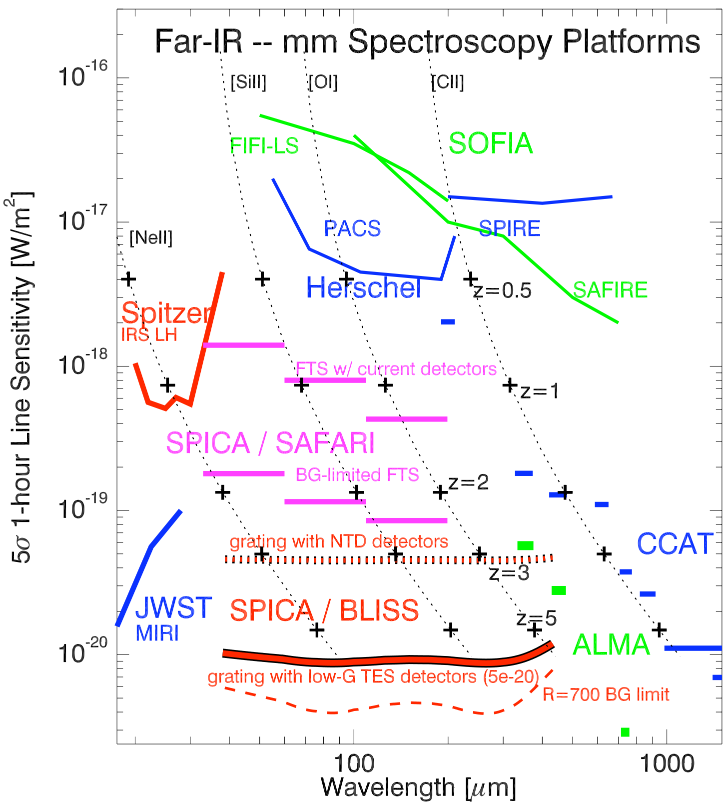


Figure 4: Sensitivity of far-IR spectroscopy platforms. (Observing speed scales as the inverse square of the sensitivity). All values were obtained from web pages and relevant literature. The red SPICA-BLISS curves are calculated assuming a 3.5-meter telescope with 75% aperture efficiency and 25% total instrument transmission in a single polarization. Sky backgrounds are average values appropriate for the North Ecliptic Pole. The light dashed curved at bottom shows the photon background limit, the heavy curve above it assumes a detector noise-equivalent power (NEP) of $5 \times 10^{-20}\,\mathrm{W\,Hz^{-1/2}}$, achievable with transition-edge superconducting bolometers. The dotted upper red curve shows the performance possible with demonstrated semiconductor-sensed bolometer technology. As a guide to the astronomical capability, overplotted are spectral line intensities from ULIRG at various redshifts assuming a fractional line intensity of 10^{-3}, a median value in the local universe, and the current cosmology ($\Omega_{vac} = 0.73$, $\Omega_{mat} = 0.27$, $H_0 = 71$).

The far-IR remains a frontier with huge potential improvements because existing far-IR spectroscopy platforms operate far from the ultimate sensitivity limitation: photon noise from the zodiacal dust and Galactic cirrus. In regions of low zodi and cirrus, the photon noise on a cold (sub-6 K) telescope can be up to four orders of magnitude lower than that produced by a passively-cooled ($\sim$80 K) telescope (Figure 4). This translates into factors of 10^4–10^6 speed improvement in obtaining a complete spectrum for a distant galaxy.

3.1 The BLISS Spectrograph

The philosophy of BLISS is to optimize capability for spectroscopic follow-up of distant (=unresolved) galaxies with unknown redshifts. Key design parameters are therefore ultimate sensitivity and total instantaneous bandwidth. For suitable detectors, the most sensitive approach is a diffraction grating, where the photon bandwidth on a single detector is comparable to the spectrometer resolution. This is the approach for BLISS, and *we emphasize that its excellent point-source sensitivity is complementary with the 2-D survey capability of SAFARI, a Fourier-Transform instrument proposed by the European consortium, which will find interesting objects for detailed study with BLISS.*

A single grating spectrometer only efficiently couples a single octave of bandwidth, so the full BLISS instrument is a series of spectrometer modules. Design details are being iterated, pending the physical resource availability of the observatory, especially cryogenic mass. The

Table 2: BLISS Instrument Bands, Modules Sizes, and Detector Formats

Band	λ_{min} μm	λ_{max} μm	L cm	W cm	H cm	N_{det}	Spat. Pitch μm	Spec. Pitch μm
Cross-dispersed echelle modules								
1	38	67	10.3	6.6	6.0	480 ×2	306	193
2	67	116	18.0	11.5	11.0	480 ×2	535	337
WaFIRS modules								
3	116	180	14.9	14.9	3	384 ×2	873	140
4	180	280	23.1	23.1	4	384 ×2	1353	216
5	280	433	35.9	35.9	4	384 ×2	2097	336
Total Envelope, both beams								
	38	433	50	50	50	4224		

working BLISS concept (Table 2) is five bands covering the 38–433 μm range at $R \sim 700$, all coupling the same position on the sky through the use of a polarizer and dichroic filters. This single 'bank' of five spectrometers is duplicated so the full instrument couples two adjacent sky positions, separated by 1–2 arcminutes (2–3 beams at the longest-wavelength). The light from the astronomical source is exchanged between the two spectrometer banks with a cryogenic chopping mirror at a frequency of 0.5–5 Hz. This provides the necessary modulation for the bolometers, and because the source is observed by both banks of spectrometers, offers redundancy against losing a spectral channel entirely if a detector in one bank fails. The chopper is at an image of the secondary to minimize differential spillover between the chop positions, and is curved to eliminate collimating mirrors and reduce aberration and cross-polarization.

BLISS will employ two types of broadband grating (Figure 3.1). The WaFIRS system demonstrated at $\lambda = 1$ mm in the Z-Spec instrument [16, 17] on Mauna Kea will be used for the longer wavelengths (bands 3, 4, 5), where the conventional modules would be prohibitively massive. WaFIRS is a 2-D system which uses a custom-machined curved grating in parallel plate waveguide— it offers a very compact size and minimum mass. The WaFIRS modules require fabrication and assembly of waveguide parts with tolerances on order $\lambda/20$, so they are not suitable for the short wavelengths. For the two short-wavelength bands, BLISS will employ conventional cross-dispersed echelle grating modules, similar to those used for the high-resolution modules of the Spitzer infrared spectrograph (IRS) [18], but with a new maximally-compact design. Each WaFIRS module will have 384 detectors arrayed along the focal arc, while for the echelle spectrometers, the 480 detectors are assembled in 1-D strips of a 2-D plane to match the positions of the grating orders. The active absorbing area on each detector ranges from 190×310 μm for the shortest-wavelength band to 2100×340 μm for the longest-wavelength band. The total number of detectors required is 4224, and we baseline transition-edge superconducting (TES) bolometers (Figure 9 and Section 4.1), read out with a sub-Kelvin multiplexer in groups of 32 (Figure 10 and Section 4.2).

3.1.1 BLISS Systems Design, Refrigerator

To approach the photon background limit, the TES bolometers envisioned for BLISS must be cooled to 50 mK, and the system will have stringent stray light, EMI mitigation, and

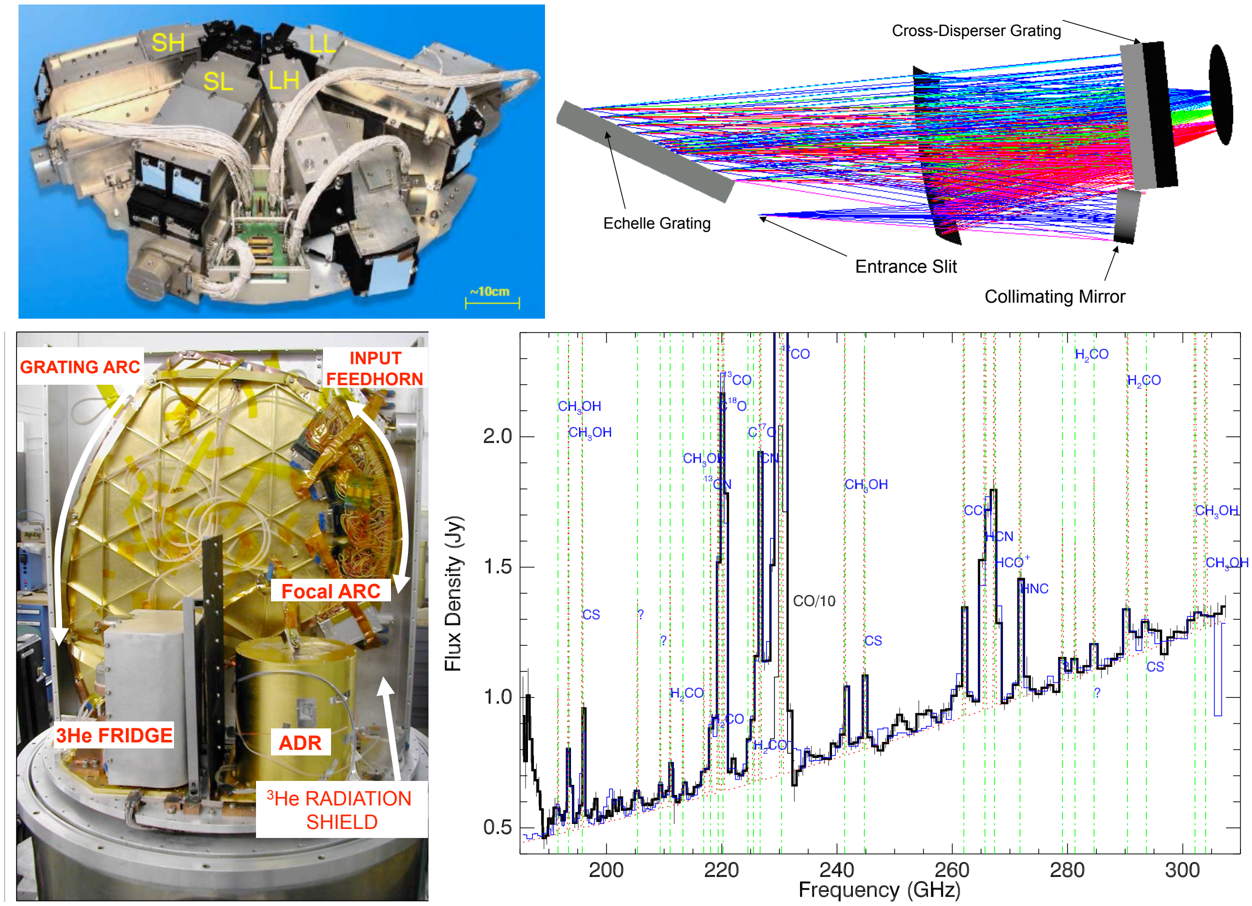


Figure 5: BLISS spectrometer module heritage. The very-successful Infrared Spectrograph (IRS) on Spitzer is shown in the (top, left) [18]. It consists of four cross-dispersed echelle grating modules, two low resolution (R$\sim$100) covering 5–38 μm, and two high resolution (R$\sim$600) covering the 10–38 μm. Spectrometer sizes scale as $\lambda \times R$, and these IRS designs are too large when simply scaled to the far-IR, but (top, right) shows the more compact design developed for BLISS bands 1 and 2 using the same principle. For the longer wavelengths, a new approach is required. We have developed the Waveguide Far-IR Spectrometer (WaFIRS) which uses parallel-plate waveguide propagation and curved grating operated in 1st order. Our prototype instrument (Z-Spec) for the 1 mm band at the Caltech Submillimeter Observatory in shown in the lower left. Z-Spec provides R=300 over the 1–1.6 mm band in a 50 cm package which is essentially two-dimensional. The entire spectrometer is cooled to 60 mK with an adiabatic demagnetization refrigerator (ADR) to provide background-limited performance. The instrument is now working routinely at the observatory, providing the first broadband spectra in its waveband. An example, the nucleus of the starburst galaxy NGC 253, is shown in the lower right (Lieko Earle et al., in preparation). Both spectrograph architectures consist of machined aluminum parts in a bolted construction with no moving parts.

thermal performance requirements. BLISS thus uses a multi-stage approach as shown in Figure 6. Mounting to the 4.5 K SPICA instrument bench is a 1.7 K stage which houses the sub-Kelvin refrigerators (Section 4.3) which in turn supports a 400 mK thermal intercept stage, from which the spectrometer modules themselves are stood off. A radiative and electromagnetic shield encloses each stage, and titanium support members connect them with sufficient mechanical rigidity and thermal isolation. We have analyzed the thermal and mechanical concept in detail, including all known thermal loads to 50 mK and the operation

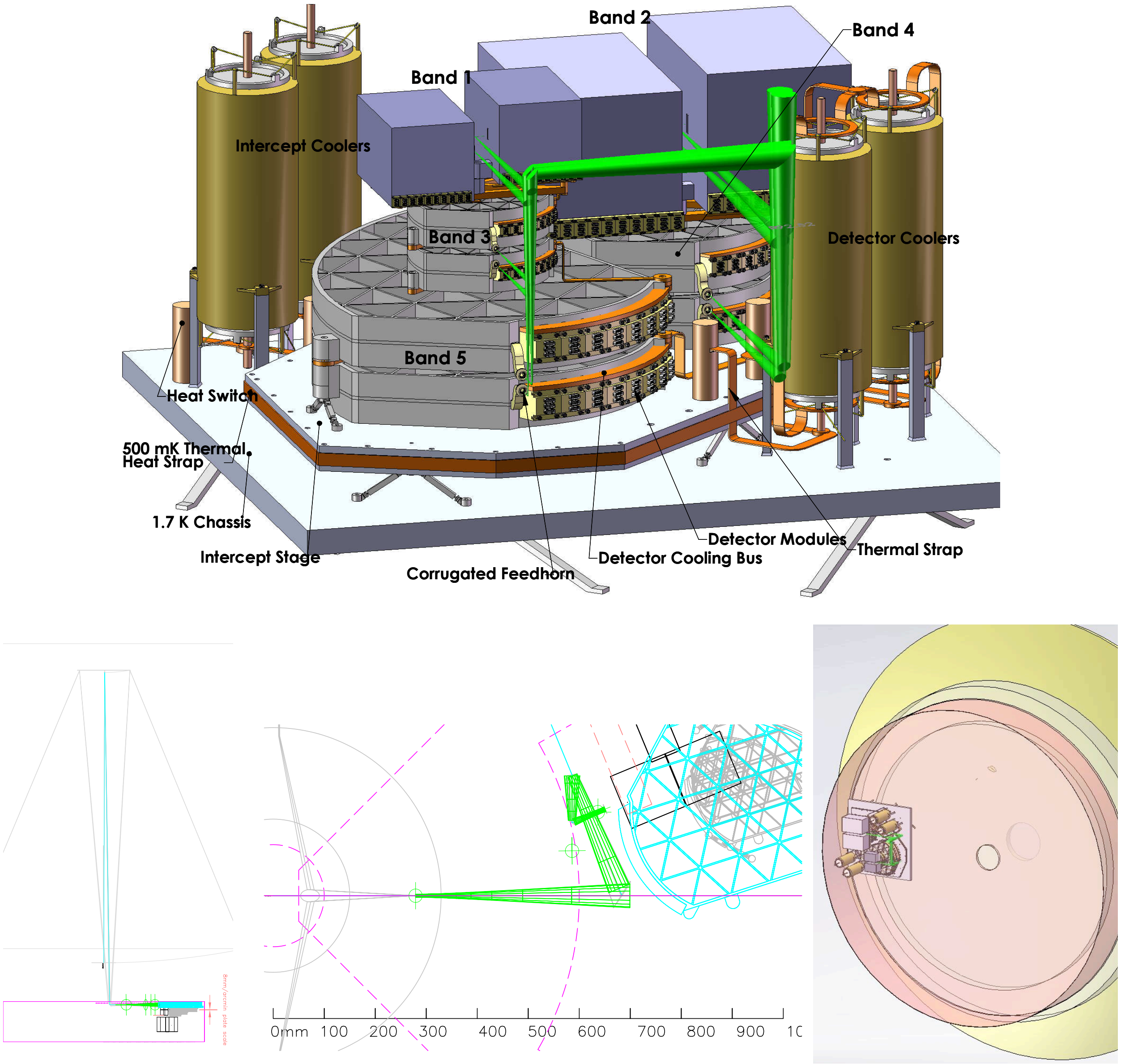


Figure 6: Top: Proposed BLISS layout, dimensions are ~ 50 cm × 40 cm × 40 cm. Ten total spectrometers cover two sky positions in 5 bands. The two shortest-wavelength bands use the conventional cross-dispersed echelle spectrometer in the lower left. For the longer wavelengths, the 2-D waveguide grating is used. For both the linear dimensions scale with $\lambda \times R$. A polarizer separates the incident light into two polarizations, one feeding bands 1, 3, 5, the other bands 2, 4, through the use of dichroic filters. (The input beams are shown schematically in green with slow $f\#$ for clarity; the polarizing and dichroic beamsplitters are not shown.) Radiation shields on the 1.7 K and 500 mK stage are removed for clarity. Bottom: configuration of BLISS inside the SPICA 2.5-m × 40-cm instrument enclosure beneath the 3.5-m telescope. A pickoff mirror relays an off-axis field through the chopping mirror (the 3rd mirror beginning with the pickoff = the top mirror in the middle figure) to BLISS, which will sit some distance from the telescope boresight. The pickoff and instrument offsets allows the shorter-wavelength instruments to access the central boresight region. Left is side view including telescope optics, center is looking through the telescope primary at the instrument enclosure. Right is an isometric view of the BLISS instrument within the SPICA instrument enclosure.

Table 3: BLISS Technical Heritage

BLISS Technology	TRL	Heritage	Minimum Instrument Technology	TRL	Heritage
Echelle spectrometer	9	Spitzer IRS			
WaFIRS spectrometer	6	Z-Spec			
TES bolometers	4	SPT, ACT, GISMO	NTD Ge bolometers	6–9	Herschel–SPIRE, Planck–HFI
SQUID multiplexer	6	ACT, SCUBA2, GISMO	JFETs	9	Herschel–SPIRE, Planck–HFI
Warm multi-channel electronics	6	ACT, SCUBA2, GISMO	AC-biased low-noise amplifiers	9	Herschel–SPIRE
Dual-stage continuous ADR	5	Suzaku–XRS	Dual-stage single-shot ADR	9	Suzaku–XRS
Cryogenic chopping mirror	9	Herschel–HIFI, Spitzer–MIPS			

of the refrigerator to insure that it can be achieved. The cryogenic mass of the current BLISS concept is ∼50 kg (including margin), and it requires a heat lift from SPICA's facility 1.7 K cooler of 5 mW, well within its capability.

3.1.2 Minimum Instrument

Achieving the goal performance for BLISS requires the technology program described in Section 4, but we emphasize that we could begin construction today on an extremely capable spectrograph using demonstrated flight-ready technology. We have developed a complete instrument design named based on the semiconductor-sensed bolometers (known as NTD Ge bolometers) now observing in space on Herschel and Planck. These devices are extremely robust and well-characterized, and as Figure 4 shows, can provide sensitivity improvements of 2–3 orders of magnitude relative to Herschel, and remains more sensitive than SAFARI. Array format is limited, but still sufficient to cover the far-infrared band at R=200–300; higher than the successful and widely-used low-res spectrograph modules on Spitzer. Instead of the continuous 50 mK refrigerator, we would use a single-shot configuration similar to that demonstrated in the XRS on the Suzaku mission.

3.2 Responses to Questions

3.2.1 Description

Describe the proposed science instrumentation and state the rationale for its selection. Discuss the specifics of the instrument. See Section 3.1

Table 4: BLISS Instrument Parameters, Resource Requirements

Item	Value	Unit
Type of instrument	Far-IR grating spectrometer	
Number of channels	4224 pixels, 2 spat × 2112 spec	
Dimensions	50×40×40	cm
Cryogenic mass (CBE w/ margin)	**53**	kg
Optics & detectors (10 spectrometers, detector blocks)	18	
Shields & supports (4 K, 1.7 K chassis, rad. shields, Ti struts)	9.5	
Preamps / cold MUX	1.7	
50 mK ADR fridge (magnets, salt pills) + copper heat straps	4.9	
Thermal ballast	3	
Cryogenic mass margin (30%)	12	
Wiring harness mass (CBE w/ margin)	**17**	kg
Data + housekeeping wiring (1682 wires)	7.3	
Data + housekeeping connectors (1682 wires)	5.5	
ADR high-current harness (8 leads)	1.4	
Wiring harness mass margin (30%, not on connectors)	2.6	
Warm mass (electronics & packaging) (CBE w/ margin)	**31**	kg
Readout electronics and housing	16	
Chopper / ADR drive / housekeeping electronics + housing	7.7	
Warm mass margin (30%)	7.1	
Total instrument mass (CBE w/o margin)	**79**	kg
Total instrument mass (CBE w/ margin)	**101**	kg
Instrument power in operation (CBE w/ margin)	**78**	W
Power system	12	
Sub-K cooler drive	10	
Housekeeping	8	
Readout electronics	30	
Chopper drive	1	
Instrument power margin (30%)	18	
Instrument power in standby mode (CBE)	**16**	W
Maximum data rate	**6**	Mbits / sec
Pointing requirements (knowledge & control)	**0.67**	arcsec RMS
Pointing stability	$\mathbf{10^{-3}}$	arcsec / sec

3.2.2 Technical Maturity

Indicate the technical maturity of the major elements and the specific TRL of the proposed instrumentation. Table 3 presents the TRL for the key elements of the goal instrument for BLISS as well as the minimum instrument. A few notes follow:

- Both types of grating spectrometer proposed for BLISS have been fielded in astronomical instruments. The conventional echelle spectrometers have been flown on the Spitzer mission, making them TRL 9; the WaFIRS spectrometer has been fielded in the Z-Spec instrument which has been deployed at the Caltech Submillimeter Observatory and is now in regular use producing scientific results, making it TRL 6. Both approaches are simple bolted-aluminum structures, making flight qualification straightforward.

- The transitions-edge superconducting (TES) bolometers for BLISS represent extension of technology which is being fielded in ground-based and sub-orbital instruments. While the system noise required for the BLISS detectors is lower than in previous implementations (see Section 4.1), most of the systems aspects have been addressed in these existing experiments, making them TRL 4. We do note that sub-Kelvin bolometer arrays made by JPL but using a different readout scheme now have flight heritage (TRL 9) in Herschel and Planck, and provide a high-reliability fallback approach forming the basis of the 'minimum instrument.'

- The multiplexing readout (MUX) uses a cryogenic switched SQUID circuit, and has been demonstrated in several ground-based and sub-orbital instruments (see Section 4.2), making it TRL 6.

- The continuous 50 mK cooler for BLISS is an extension of flight demonstrated single-shot system (see Section 4.3), but it requires development of a 50 mK thermal switching capability, making it TRL 5.

- The cryogenic chopping mirror required for BLISS is very similar to that flown on the Herschel HIFI instrument, making it TRL 9.

3.2.3 Technical Issues / Risk Areas.

In the area of instrumentation, what are the primary technical issues or risks? We list the important risks below, and present them in a risk matrix in Figure 3.2.8

1. The primary risk in the current program is **achieving optimal detector sensitivity.** However, the degradation of the instrument performance with reduced sensitivity is graceful, and a very capable instrument can be built with demonstrated technology. **Probability: 3, Impact: 2**

2. An important risk to the overall success of BLISS on SPICA will be the **SPICA - BLISS systems engineering and interface management.** Mistakes in systems engineering and interface control could result in a broad range of problems such as: excess stray light contamination from the telescope or instrument enclosure, poor performance of the BLISS refrigerator if interfaces are too warm, or electromagnetic interference, any of which would compromise the instrument sensitivity. We have budgeted extra effort in the systems engineering and I&T to help mitigate this risk. **Probability: 3, Impact: 3**

3. **The thermal performance of the BLISS refrigerator** presents risks. Failure of a heat switch or the introduction of a thermal short (for example a salt pill in a magnet bore) could limit the instrument duty cycle, or reduce the sensitivity greatly. While the impact would be high, the risk probability is low since there are no moving parts and extensive testing of these components will be conducted before integration. **Probability: 1, Impact: 4**

4. **Superconducting detectors and circuits are very susceptible to magnetic pickup**, which could reduce the system sensitivity. This is one of the key issues

affecting the ground-based and suborbital experiments now being deployed. Most of this is due to modulation of earth's field in scanning experiments. The ambient field at L2 is 5 nT, 10,000 times smaller than earth's field, so for BLISS the emphasis will be in shielding fields generated by the instrument and spacecraft. Of course, we envision a detailed test program during instrument development and I&T, and magnetic interference can be tested with the other instruments and mechanisms in a high state of integration pre-launch. We also note that magnetic pickup can be mitigated with high-permeability shielding, which adds mass but is straightforward. **Probability: 2, Impact: 3**

5. Developing a **flight-qualified multiplexer and readout electronics** suitable for SPICA is a cost and schedule risk, though cryogenic SQUID-based circuits have flown on three space missions since 1992, including Gravity Probe B. **Probability: 2, Impact: 2**

6. **Stray light contamination** is a risk for an ultra-sensitive thermal infrared instrument such as BLISS. Stray light can degrade the instrument sensitivity. We are incorporating several measures to mitigate this risk. Both the WaFIRs and echelle spectrometers are completely closed architectures, so that the detectors only see out of 50mK through the input feedhorn (for the WaFIRS) or the entrance slit (for the echelle). Furthermore, completely sealed radiation shields are incorporated on both the 500 mK and 1.7 K stages. **Probability: 2, Impact: 4**

7. **Detector yield** is always a risk, especially since the BLISS detector arrays do not oversample the spectral profile (as they do with, e.g. the Spitzer IRS). However, by using dual spectrometer banks, this risk is largely elimated. If a single detector fails in on spectrometer bank, that frequency is still observed in the second bank. **Probability: 3, Impact: 2**.

3.2.4 Instrument Table

Fill in the entries in the Instrument Table. See Table 4.

3.2.5 Contingencies

If you have allocated contingency please include as indicated along with the rationale for the number chosen. We carry 30% margin for all quantities except mass of the wiring harness wires themselves, for which the margin is 15%. (Masses of connector still carry 30% margin.)

3.2.6 Payload Table

Fill in the Payload table. All of the detailed instrument mass and power entries should be summarized. We have incorporated the BLISS mass breakout in the instrument table (Table 4).

3.2.7 Responsible Organizations.

Provide for each instrument what organization is responsible for the instrument and details of their past experience with similar instruments. JPL will be solely responsible for all aspects of BLISS design, fabrication and assembly. JPL scientists and engineers will of course also support the integration with SPICA at ISAS / JAXA in Sagamihara, Japan. Our organization has recently delivered the world's most sensitive far-IR / submm flight focal planes (Herschel SPIRE and HIFI, Planck HFI, LFI) and is leading ground-breaking ground-based and sub-orbital experiments using the new detector technologies (Z-Spec spectrometer, BICEP-2, Spider, MKID-cam). We are planning a consulting arrangement with the NIST team led by Kent Irwin who has developed the cryogenic multiplexers (we are working with them on sub-orbital experiments.) We also note that we are discussing potential cost and mass-sharing approaches with the European team developing SPICA: for example sharing the sub-Kelvin refrigerator.

3.2.8 Previous Studies

Describe any concept, feasibility or definition studies already performed. BLISS was originally funded by NASA as an Origins Probe concept study in 2004. This allowed us to define the instrument concept and begin a dialog with the SPICA study team about both technical issues: thermal, mechanical, and optical interfaces; and programmatic issues such as time allocation and data access. It resulted in a report in 2005[¶] We have continued working with the Japanese and refine the instrument approach at a low level, and have been awarded NASA funds for BLISS detector development. Subsequently, the minimum mission (see Section 3.1.2) was proposed to the 2008 Small Explorer (SMEX) call as a mission of opportunity,[‖] receiving excellent scientific reviews (see Section 6.1).

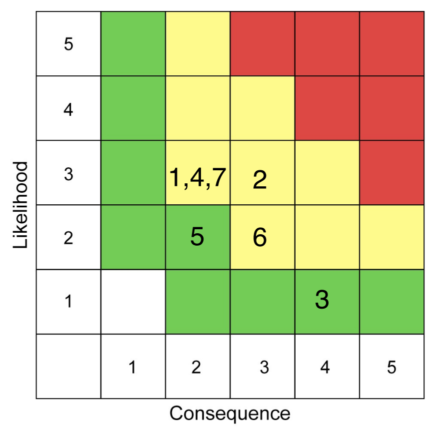


Figure 7: BLISS risk matrix.

3.2.9 BLISS Instrument Modes.

Provide a functional description of operational modes, and ground and on-orbit calibration schemes. BLISS has a single very simple observing mode: the spectrographs simply stare at the sky, and the astronomical source is exchanged between the two banks of spectrometers with the cryogenic chopping mirror at a frequency of 0.5–5 Hz. Analyzing the datastream to extract science data will involve only simple demodulation and co-addition against the chopper encoder. In the event of chopper failure, BLISS can operate in a drift-scan mode, in which the telescope simply drifts the BLISS beams across the sky. Calibration in flight will be performed by observing astronomical sources with the same mode as for the science observations, in a manner similar to that used on e.g. Spitzer. For all modes, the detectors will be read out with a bandwidth of 30–100 Hz and co-added to 5 Hz sampling in firmware. When BLISS is observing, the maximum data rate is 4224 detectors x 5 Hz x 14 bits depth = 0.5 Mbits / sec. Integrated over the 5-year lifetime of the mission, assuming BLISS operates

¶available at `http://www.submm.caltech.edu/~bradford/BLISS/BLISS-report-final.pdf`

‖available at `www.submm.caltech.edu/BLISS`

25% of the time, the total estimate data volume is 1.5 Terabytes.

3.2.10 Flight Software.

Describe the instrument flight software, including an estimate of the number of lines of code. BLISS flight software would be fairly straightforward, with just a few major components:

- Command processing, which just passes spacecraft commands through to the electronics FPGA
- Science data processing, to produce calibrated, de-glitched bolometer time stream data.
- Engineering telemetry, with packetized transmission to the spacecraft
- Minimal fault protection
- Cooler control, consisting of simple current ramps, possibly with very low-bandwidth control for temperature stabilization.

Because the software functional requirements are limited, no operating system should be needed, and flight software can communicate with the instrument and spacecraft through a memory-mapped electronics interface. Code could execute from non-volatile memory, with RAM-based patchability. Fault protection would be very basic, with only simple algorithms to protect the health of the instrument as needed. We estimate a total of 5000 logical lines required for BLISS flight software.

3.2.11 Non-US Participation.

Describe any instrumentation or science implementation that requires non US participation for mission success. SPICA is proposed as a Japanese-led mission with substantial participation from both ESA (for the telescope) and the European national agencies (for the SAFARI instrument). Clearly, the program success depends on the JAXA and ESA elements performing as expected, but they are beyond the scope of the BLISS instrument. No non-US elements are required for the BLISS instrument itself.

3.2.12 Master Equipment List.

Please provide a detailed Master Equipment List for the payload. A MEL for the SPICA mission is beyond the scope of this RFI, but we breakout the key components of the BLISS instrument in Table 4.

3.2.13 Flight Heritage.

Describe the flight heritage of the instrument and its subsystems. All elements except those explicitly mentioned above (Question 2) have flight heritage, and we emphasize that a very capable instrument could be built with flight-proven technologies without any further development (see Section 3.1.2). However, we have planned and budgeted a 24–30-month development plan to deploy the most sensitive instrument (Section 4).

3.3 Technical Implementation: SPICA Mission and Spacecraft

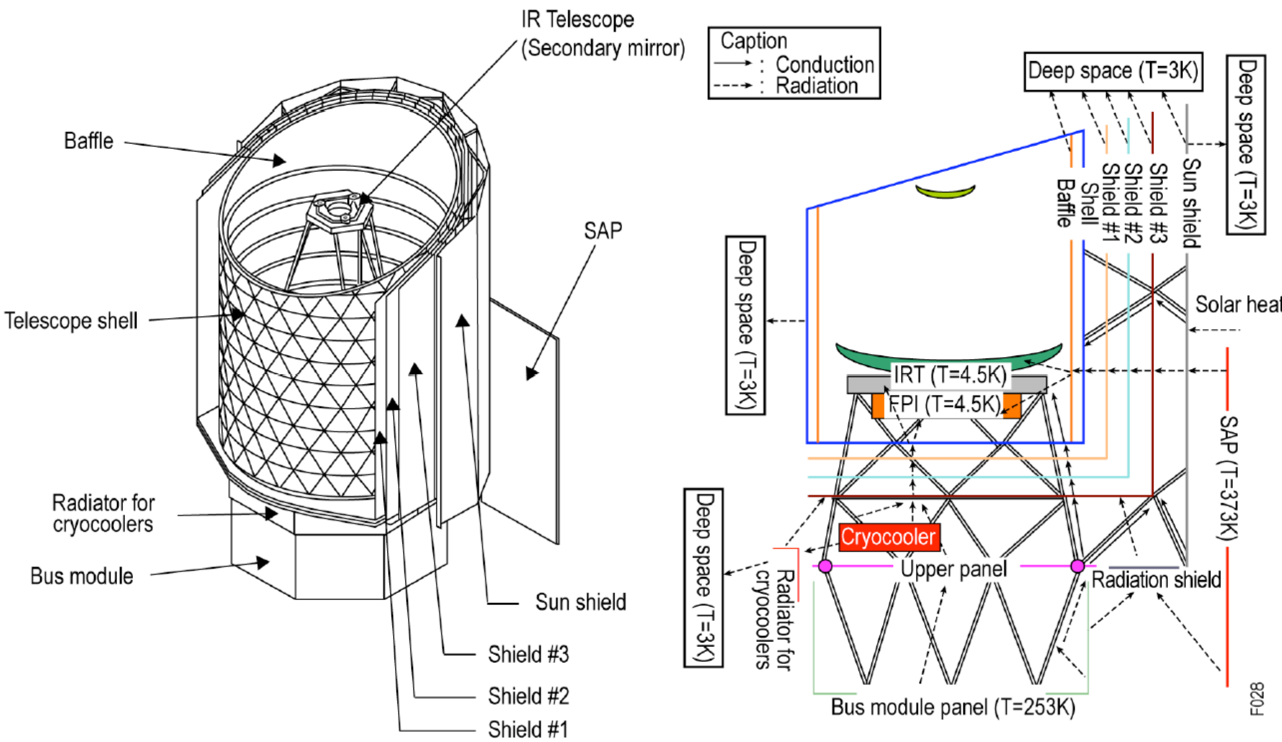


Figure 8: SPICA Spacecraft and Thermal Design

While not the focus of this RFI response, we provide an overview of the SPICA mission. SPICA is being led by the Japanese infrared astrophysics community and their space agency JAXA (Japanese Aerospace and Exploration Agency). Prof. Takao Nakagawa is the PI, and details can be found in his articles [19, 20]. SPICA builds on the heritage of previous Japanese cryogenic missions, especially AKARI, but will include several advances which facilitate the 3.5-m, 4.5-K aperture, and enable the 5-year mission:

1. SPICA will employ a warm-launch architecture, similar to that used with Spitzer, substantially reducing the cryostat mass and volume. A careful system-level thermal design employs radiative cooling to minimize the the loads on the active 20 K and 4 K stages. More information on the SPICAs cryogenic design can be found in [21].

2. Closed-cycle coolers will be used instead of a liquid cryogen vessel to provide the low-temperature cooling. Joule-Thomson (JT) coolers will provide the 4.5 K base, with support from two-stage Stirling coolers at 20 K. To support focal-plane instruments, an additional ^{3}He JT stage with lift of more than 10 mW at 1.7 K will also be employed. These cryocoolers are the enabling technology for the observatory, and JAXA's investments in this area have proven very successful in the AKARI coolers [22] and demonstrated prototypes for SPICA [23].

3. SPICA will operate at the Earth-Sun 2nd Lagrange (L2) point, simplifying the shielding and maximizing the effectiveness of radiative and active cooling.

Table 5: SPICA Spacecraft and Mission Parameters

Parameter	Value	Unit
Orbit configuration	Earth-Sun L2 halo	
Launch date (current plan)	2017	
Launch vehicle	JAXA HIIA	
Mission lifetime	5 years requirement, 10 year goal	
Telescope diameter	3.5	m
Telescope configuration	2-mirror on-axis Ritchey-Chrétien	
Telescope effective focal length (baseline)	20	meters
Primary-secondary mirror separation (baseline)	3	meters
Telescope back focus (baseline)	0.8	meters
Field of view	24 (rqt) 30 (goal)	arcsec diameter
Telescope image quality	Diffraction-limited at 5 μm	
Telescope surface roughness	< 20	nanometers RMS
Telescope mirror reflectivity	$>$97.5% for $\lambda > 30$ μm	
Telescope attitude control	under study	
Telescope mass accommodation	$<$700	kg
Telescope stiffness requirement	$>$60 Hz (z-axis), $>$30 Hz (x,y axes)	
Telescope temperature	6 (rqt), 5 (goal)	degrees Kelvin
Telescope temperature stability	$<$0.25	K / h
Telescope temperature uniformity	$<$0.5 K across primary	
Volume available for scientific instruments	Cylindrical, 2.5 m dia $\times$ 0.5 m height	
Power available for scientific instruments	200	Watts
Cryogenic mass allocation for scientific instruments	150	kg
Heat lift at 4.5 K available for instruments	15	mW
Heat lift at 1.7 K available for instruments	5	mW
Data handling for scientific instruments	4 Mbits per sec, 60 GBytes per day	

SPICA's telescope is under ESA-funded study in Europe: the baseline concept is to employ the silicon carbide technology developed for Herschel [7]. Several focal-plane instruments are under study for SPICA in addition to BLISS; it is anticipated that these instruments would be available to US observers as part of the partner open time.

4 Enabling Technology: Development Program

We plan a technology program to realize the full scientific capability of SPICA's cold telescope, aiming to achieve background-limited sensitivity for far-infrared spectroscopy. The technology program benefits SPICA scientifically, and also enhances US capabilities by providing a targeted application for which to aggressively pursue the detector and cooling technologies needed for SAFIR/CALISTO and SPIRIT. This program is analogous to US development program for the SPIRE and HIFI instruments on Herschel, where cutting-edge technologies were developed and selected based on readiness dictated by the Herschel schedule. We reiterate that, as described in Section 3.1.2, a very capable instrument could be built even if the program does not realize all of its goals.

The emphasis of the technology program is to demonstrate that detector and cooling *systems* are compatible with SPICA. TES bolometers have already demonstrated the required thermal isolation and heat capacity, and higher NEP analogs are currently carrying out scientific observing programs. Larger format SQUID multiplexers are already in use in ground-based instruments. The sub-K coolers have been demonstrated in space in single-shot configurations. The issue is to take these component technologies and demonstrate an instrument which is compatible with the cooling, EMI, and optical interfaces presented by SPICA. The technology program will ultimately produce a development model with background-limited detectors, which is tested with these interfaces.

4.1 High-Sensitivity Bolometers

The target sensitivity for BLISS detectors is a noise-equivalent power of NEP $= 5 \times 10^{-20}\,\mathrm{W\,Hz^{-1/2}}$. The most suitable approach given SPICA's timescale is to array superconducting transition-edge-sensed (TES) bolometers with a SQUID-based multiplexing readout (MUX). Thermally and mechanically, the detector itself derives from from the micro-mesh bolometer—a silicon nitride membrane patterned into a grid absorber suspended by thin legs from the thermal bath. These devices have shown excellent overall performance with semi-conducting sensors, and are now flying in Herschel and Planck.

The addition of the TES sensor offers the potential for larger array formats through the MUX, and higher sensitivity through reducing the detector response time. This technology has matured steadily, and kilo-pixel TES arrays are being widely used (see Section 4.2).

To approach the background limit for space spectroscopy, one must reduce the intrinsic temperature-fluctuation noise due to phonon fluctuations between the absorber and the thermal bath: $\mathrm{NEP_{phonon}} \simeq \sqrt{4\mathrm{kT^2G}}$, where G is the thermal conductance between the absorber and bath, T is the bolometer temperature. For a 50 mK base temperature available with current cooler technology, one must reduce G to $\sim$10 fW/K to approach the BLISS photon NEP. The device in Figure 9 achieves this. The suspended absorber is connected to the substrate through four $\mathrm{Si_xN_y}$ support beams. The low value of G is obtained by making the aspect ratio (length to the cross-sectional area) of the support beams very large [25]. red to about 10 fW/K[25]. Noise measurements with a TES at 220 mK confirm the thermal noise, and the lower-T superconducting films are under fabrication now to demonstrate the ultimate sensitivity.

The response time of existing devices is 100 ms, using the natural electro-thermal speedup

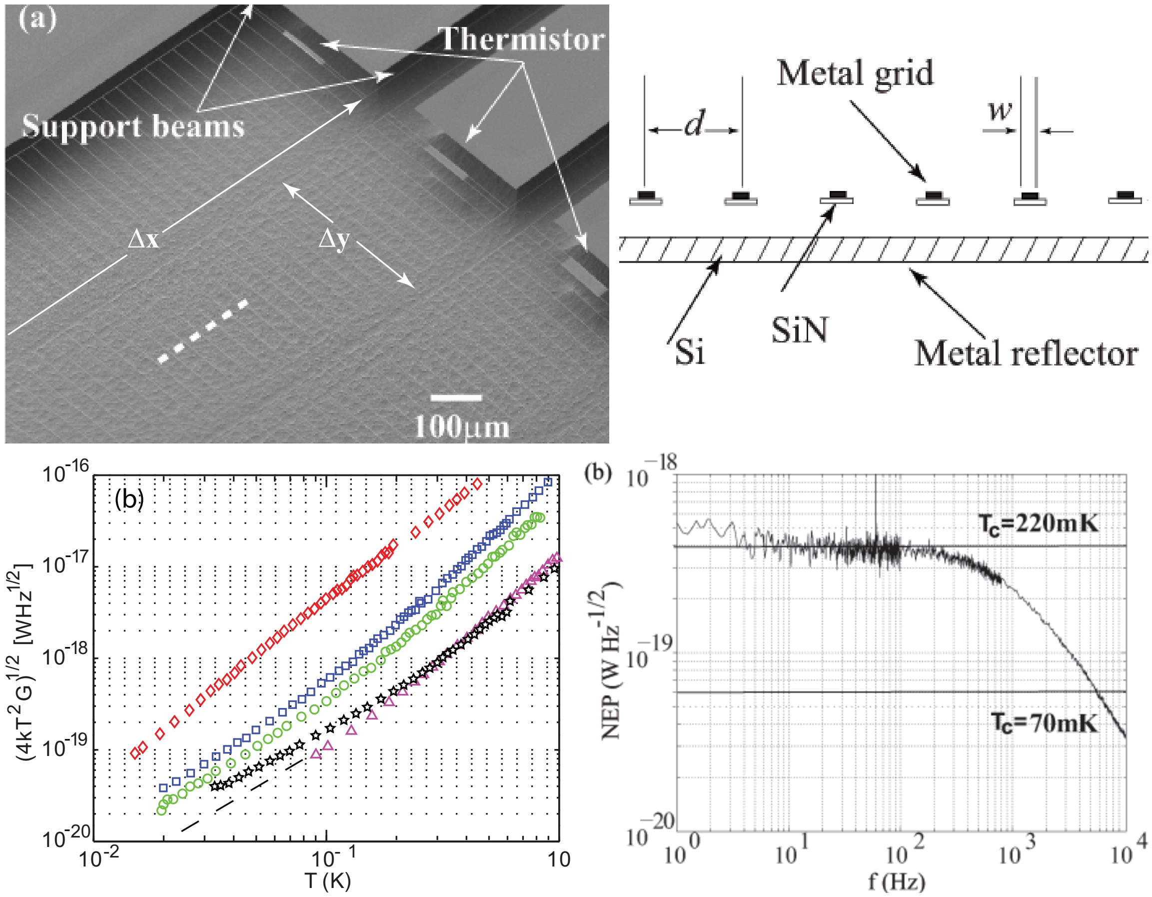
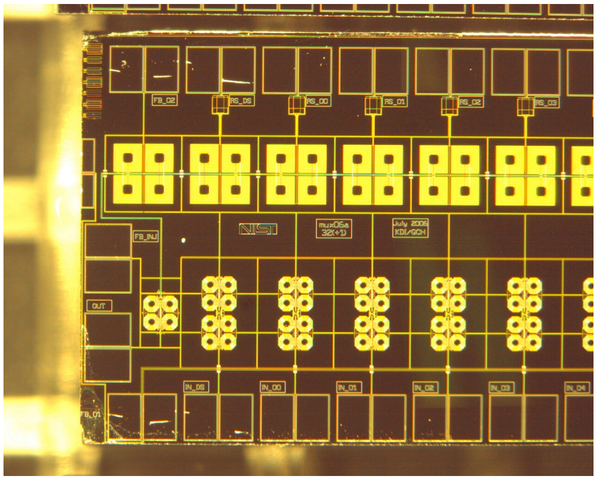


Figure 9: Results in low-G TES development. (Top, left): A TES array segment designed for the long-wavelength module of BLISS showing 3 detectors side by side. Each absorber is $\Delta x = 300\,\mu$m wide by $\Delta y = 2000\,\mu$m long, and the support beams are $1000\,\mu$m long by $0.25\,\mu$m thick by $0.4\,\mu$m wide (beams extend beyond figure). A thin gold film deposited onto the absorber rungs matches the sheet impedance of the device to that of free space, and when combined with a quarter-wave backshort, the absorption efficiency can exceed 80%, as demonstrated with the Herschel and Planck bolometers. (Top, right): an edge-on schematic view of the absorber and backshort construction. (Below, left): Measured thermal conductance (G) data plotted in units of detector noise equivalent power (NEP), showing that we have achieved thermal isolation sufficient for sensitivities well below $10^{-19}\,\mathrm{W\,Hz^{-1/2}}$. The symbols correspond to various beam geometries; the stars represent a device similar to the one shown above. (Below, right): Noise measurement of a leg-isolated device at 220 mK; results are as predicted from the G data. Operated at $T_C = 70\,$mK, the device will realize NEP $= 6 \times 10^{-20}\,\mathrm{W\,Hz^{-1/2}}$.

of the TES. Improvements are expected, but this is adequate for BLISS since the instrument operates in a simple chopping mode. Similarly, the device's natural dynamic range is ~1000, ample for extragalactic observations, but can be extended to 10^5 with the use of a second, higher-temperature TES film in series, a technique successfully used in the Keck experiment (see Figure 10) dual TES.

4.2 Superconducting Multiplexer

The pixel count for BLISS makes it essential to multiplex the bolometer signals at the cold stage. Fortunately, over the past several years, technology for cryogenic multiplexing of TES



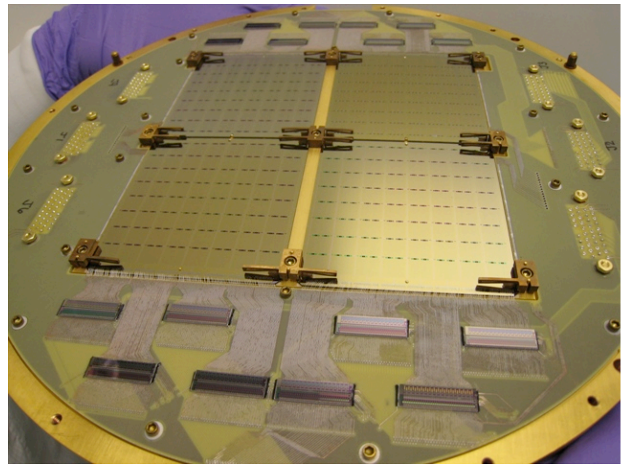


Figure 10: LEFT: Photo micrograph of a portion of a working 32-channel time-domain SQUID multiplexer (TDM) from NIST Boulder. Eight channels are shown. RIGHT: A 512-pixel TES focal plane for Keck, a CMB polarization experiment which uses the NIST MUX.

bolometers has matured significantly, and SQUID-based time-domain multiplexed (TDM) readouts developed at NIST Boulder are currently able to multiplex in groups of up to 40 detectors at the low-temperature stage, introducing negligible amplifier noise. TDM readouts have been / are being produced for numerous experiments (Table 6)

Table 6: Experiments Using NIST Time-Domain SQUID Multiplexer with TES Bolometers

Name	Description	Total N_{pix}	Status
MUSTANG	Ground-based 3 mm camera	64	operating
ACT	Ground-based CMB	3,072	operating
GISMO	Ground-based 2 mm camera	128→1,280	operating
SCUBA-2	Ground-based submm camera	10,240	commissioning
Keck	Ground-based CMB pol	2,336	commissioning
SPIDER	Balloon-borne CMB pol	2,624	integration
ZEUS2	Ground-based submm spectrometer	660	integration

We envision a NIST collaboration to develop a flight MUX for BLISS. The circuit will use the now-standard 32-element linear MUX architecture [26] shown in Figure 10, but with several modifications to accommodate the lower NEP of the BLISS detectors. First is a chip with lower power dissipation at the cold stage to accommodate the large pixel count and small power budget. A reduction of power dissipation by a factor of about 8 will be accomplished by reducing the critical current of the SQUID switches and increasing the SQUID input inductance and shunt resistance. We note that even in the face of the lower NEP in the bolometers, the desired SQUID parameters are not extreme, and are similar to those used in some previous SQUID designs. A second modification will be to incorporate a larger inductive filter in front of the SQUID switches, enabling a lower frequency and thus lower power dissipation in the room temperature drive electronics relative to the ground-based and suborbital experiments.

4.3 Sub-100 mK Refrigerators

The very low NEP and optical loading of the BLISS detectors requires that the BLISS focal plane modules be cooled to T$\sim$50 mK with a system that rejects heat to SPICA's 1.7 K cooler ($P_{max} = 5$ mW). The current state-of-the-art sub-K flight coolers is limited to ^{3}He sorption coolers on IRTS and Herschel/SPIRE ($>$ 280 mK in a single shot mode), the Planck open-cycle dilution refrigerator (100 mK, <200 nW, 2.5 year life due to expendables), and the Suzaku–XRS Adiabatic Demagnetization Refrigerator (ADR) (60mK, single shot). All cooled cold stages with mass <2 kg, much smaller than BLISS. Fortunately with some enhancements, both ADR and dilution approaches both will meet the needs of BLISS.

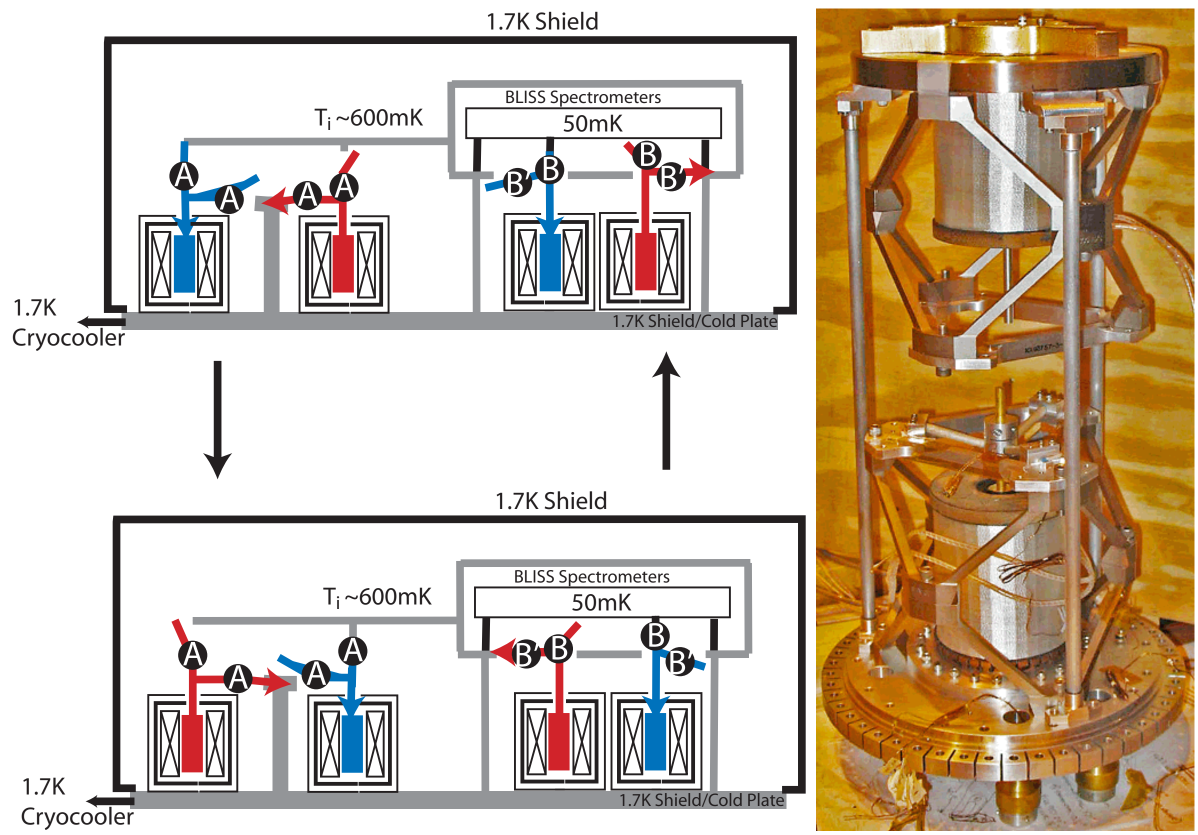


Figure 11: LEFT: Schematic of 2-stage continuous ADR envisioned for BLISS. The blue rectangles represent paramagnetic salt pills absorbing heat at operational temperature; the red indicate pills which are dumping heat while recycling to the next higher temperature stage. Arrows indicate heat flow. The upper and lower frames represent the two phases of the operational cycle. RIGHT: Prototype hardware: a single-shot dual stage system with a titanium suspension to verify salt pill performance and parasitic loads.

Adiabatic Demagnetization Refrigerators (ADRs) are ideal for a long-duration mission because only electrical power is required, there are no expendables and no moving parts. To adapt the basic approach to the needs of BLISS two advances are baselined 1) to include an intercept stage at T$\sim$500 mK, greatly reducing the load on the 50mK stage, and 2) to operate the system in a continuous mode: possible with a proper configuration of multiple salt pills and heat switches. Figure 11 shows the BLISS design and hardware prototypes, further details can be found in the SPIE paper [27], and Holmes et al. (2009).

5 Mission Operations Development

Mission operations for SPICA will be conducted by JAXA, and BLISS scientists will interface with JAXA to submit observing requests and obtain data. There are no unusual communications requirements for BLISS—like most astrophysics missions, it will use queued observing with no real-time requirements. Similarly, for pointing, there are sources distributed throughout the sky, and the long wavelengths translate to relaxed pointing requirements relative to optical / near-IR missions.

The science deliverables from the BLISS team will be calibrated spectra of ∼500–1000 galaxies per year (depending on SPICA time allocation) presented in published in articles and available to the community. We recognize that our analyses will not likely tap the full potential of the rich dataset. Our emphasis will be on producing calibrated spectra that can be used by the worldwide community, and we anticipate survey articles that will support the further use of the data. We intend to make the data available in FITS format as well as in raw-product form on a publicly-available website no later than 18 months after receipt of data products from JAXA. The data will also be in a form accessible to existing astronomy databases and archives (e.g. NED, IRSA).

To produce these spectra, we will generate a pipeline based on examination of the first 100 spectra obtained early in the mission. Based on experience of the PI and co-Is, it is anticipated that these basic science products will be calibrated to 10%, absolutely and from channel to channel across the spectrum. This level of calibration is suitable for the bulk of the astrophysical experiments envisioned for BLISS outlined in Section 2.

We have budgeted \$7.5M (FY09) to carry out this reduction and analysis in Phase-E. Over the 5-year period, this will support 5 full-time scientists at half time, including the PI and Co-Is, and and 5 postdoctoral scholars. We have also budgeted \$3.6 M over the life of the program for supporting the data storage and web interface.

5.1 Potential for US Scientific Community Involvement.

To make optimal use of the US hardware investment in SPICA, it is conceivable that NASA may opt to support further data processing and analysis by the wider US scientific community. An approach is that IPAC could enable this by providing technical support to US scientists and by providing serving as a liaison between the US community and ISAS / JAXA. A similar arrangement is now being implemented very successfully with ESA's Herschel mission. Following this working model, we envision three essential components to the effort (see also the original BLISS Astro2010 submission):

1. BLISS Instrument Support, including (i) software for instrument commanding and operations, starting during development phase; (ii) data processing software, calibration, including test phase, development and on-orbit updates; and (iii) data archiving and access.

2. Technical User Support for SPICA users in the U.S., including (i) technical support for the US community, access to data, analysis software, and information other than BLISS; and (ii) data archiving for non-BLISS data.

3. Data Analysis Funding to US community, at a level comparable to that of the US Herschel budget. We assume a similar level of US community interest.

6 Programmatics and Schedule

6.1 Organization, History, and Current Status

The team submitting this RFI has been in place for 5 years. BLISS was originally funded by NASA as an Origins Probe concept study in 2004. This allowed us to define the instrument concept and begin a dialog with the SPICA study team about both technical issues: thermal, mechanical, and optical interfaces; and programmatic issues such as time allocation and data access. As the instrument concept has taken shape, the Japanese team has expressed a commitment to operating SPICA in a modern "great observatory" style, with open time for partner nations, likely including solicitations for large legacy programs, and a finite proprietary period for any data (∼1 year), after which it becomes public.

Building on the development of the science case and the realization of the potential of the grating spectrometer approach, a NASA research grant was awarded for the development of transition-edge superconducting detectors for BLISS. This work has produced encouraging results summarized in Figure 9, and Section 4.1.

Meanwhile, the scientific interest in BLISS and in the US participation in SPICA has broadened and intensified with the resounding success of Spitzer, an 85-cm cryogenic telescope. The astronomical community now awaits science data from the ESA Herschel 3.5-m telescope successfully launched in May 2009. Herschel was enabled by key US detector technology contributions and is now demonstrating broad scientific interest by US representation in key observing program selections. SPICA represents the only planned far-infrared observatory operating in the 2020's decade after Herschel. The huge gains possible with the cold telescope are recognized, and SPICA participation is now the top priority of the US far-IR astrophysics community, as outlined in a community consensus document prepared for Astro2010 led by Martin Harwit.[**] This is the same group that has brought forward the concepts for large US-led cryogenic observatories (SAFIR, CALISTO) and interferometers (SPIRIT). Providing BLISS for SPICA is not only a huge step forward scientifically, but serves as a crucial demonstration platform for the key technologies, especially detectors and readouts, that will be required for these billion-dollar-class future flagships.

The minimum mission (see Section 3.1.2) was proposed to the 2008 Small Explorer (SMEX) call named "BASS" as a mission of opportunity. The proposal[††] received excellent scientific reviews, and the $70M instrument cost (no community support included) was confirmed by the external panel. The scientific debrief summary was:

- "The scientific goals of [BLISS] + SPICA will have high scientific impact if achieved and cannot be accomplished with Herschel or SOFIA."
- "[BLISS] + SPICA provides the unique opportunity for making a broader set of observing capability in the far-infrared available to the US community."
- "[BLISS] + SPICA fills in the spectral range between JWST and ground-based submm and mm facilities ALMA and CCAT."

At that time SPICA was not yet approved in either Japan or Europe (it is now approved and under study by both space agencies), and the SMEX schedule and cost constraints are not a good match to flagship-class instrument for a major observatory.

[**] available at `http://www.ipac.caltech.edu/DecadalSurvey/farir.html`
[††] available at `www.submm.caltech.edu/BLISS`

NASA has recently (July 2009) announced an opportunity to study possible US instrument contributions to SPICA to understand and secure the necessary spacecraft resources prior to a recommendation by Astro2010.

6.2 SPICA Organization

The SPICA team at JAXA envisions three principal bodies which will govern the mission:

- **The SPICA Steering Committee** will be in charge of all final decisions concerning the SPICA project. It will consist of members from the space agencies and PIs of the instruments. The SPICA project manager will be the committee chair. This committee will likely include sub-committees to address specific aspects.
- **The Science Advisory Committee** will review activities and provide advice to the SPICA project from a scientific standpoint. It will consist of a broad range of international scientists representing key disciplines in astronomy. The SPICA project scientist will chair this committee.
- **The Joint Systems Engineering Team** will ensure clear and cogent interface definitions and anticipate system-level problems which will might arise. It will be made up of flight engineers with various backgrounds and representing the various member countries.

The organizational structure is represented graphically in Figure 12.

Regarding the interfaces, observatory-level systems engineering will be the responsibility of JAXA, and they will produce interface documents which will govern the interfaces. The details would be worked out through negotiations involving NASA and JAXA should NASA elect to participate in the mission. We *(the BLISS team)* have worked to design an instrument with straightforward interfaces which fit within the allocations for SPICA. The key technical interfaces for an instrument like BLISS will be:

- Mechanical and optical interfaces for the BLISS optical bench and the foreoptics in the 4 K instrument enclosure.
- Thermal interface with the facility 2 K cooler.
- Mechanical, electrical, and data interfaces for the warm electronics.
- Thermal and electrical interfaces along the facility cooling chain from the warm electronics box to the 2K thermal interface, to carefully heat sink and to eliminate electromagnetic interference (EMI), for the BLISS signal and magnetic cooler wiring harnesses.

6.3 SPICA Status and Near-Term Schedule

In the last year, SPICA has entered a "pre-project phase", corresponding to a NASA Phase-A study in Japan; and ESA's Cosmic Visions program has begun funding the European consortium in their study of the SPICA telescope. While the European and Japanese partners

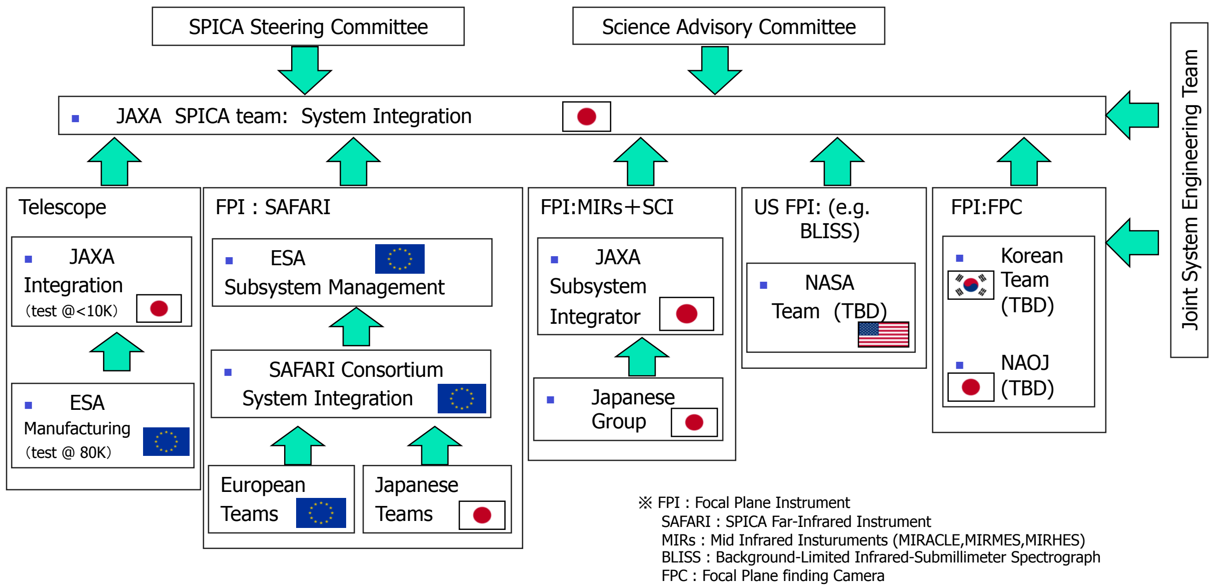


Figure 12: SPICA organizational structure, provided by mission PI Takao Nakagawa.

are interested in the U.S. far-IR capabilities, they are moving forward in the schedule shown in Figure 13 with gates and down-selects set by JAXA and ESA. The mission development will now proceed with or without US involvement, and opportunities for US participation are reduced as time passes.

JAXA and the SPICA PI have indicated that all international partners contributing key hardware must be place by the System Definition Review (SDR), scheduled for ∼January 2011. This is the technical precursor to the Project Approval Review (for management / cost) which will occur at most 6 months later. Together, the two reviews represent the go / no-go decision for SPICA in Japan, and beyond this point, major changes to the focal-plane complement and major new partnerships will be difficult or impossible.

Of course, the concept design is underway now, and instrument resource allocations (volume, mass, power) are currently being established. If the US is to have a meaningful role in the mission, we must be formally involved in these processes starting as soon as possible to preserve options for US participation. The funding requirements are very modest for this period, but an endorsement by NASA is important. It is therefore our hope that a positive recommendation from the Decadal Survey will enable NASA to initiate steps for formal US participation.

The top risks to the success of BLISS on SPICA are outlined in Section 3.2.

6.4 BLISS and SPICA Full Schedule

The schedule for BLISS is driven by working backward from the requirement to deliver the instrument to JAXA for integration with the observatory at the end of CY2015, sufficiently in advance of launch to allow full end-to-end system tests. The BLISS instrument PDR is 3 years before the required delivery, allowing 16 months each for fabrication and integration of the flight instrument, plus margin. BLISS PDR is thus in October 2012, and also aligns with

Table 7: BLISS for SPICA: Key Phase Duration Table

Project Phase	**Duration (Months)**
Phase A—conceptual design	12
Phase B—preliminary design	13
Phase C—detailed design (including BLISS instrument I&T)	34
Phase D—integration and test w/ SPICA	14
Phase E—primary mission operations	60
Phase F—extended mission operations	TBD
Start of phase B to PDR	13
Start of phase B to CDR	30
Start of phase B to BLISS delivery to SPICA	48
Integration and test, BLISS w/ SPICA	14
Total funded schedule reserve	12
Total development time phases B–D (not including margin)	62

the ESA and JAXA PDRs. **Just prior to PDR, in mid-2012, is the date for which all BLISS technology selections must be made; designs up to this point will carry multiple options** to employ the TES detectors if they are ready, but also to accommodate the semiconductor-sensed bolometers as a fall back. Of course, the instrument interfaces will be defined before this time, and the BLISS instrument designs will be tailored to provide the greatest capability for a given detector approach within the constraints of the allocated resources. Prior to technology selection and PDR is Phases A and B, is a combination of technology development and instrument design.

Per the Astro2010 instructions, we begin the costed mission cycle in phase-A in FY 2011. However, the process is starting already. As Figure 13 shows, NASA is now soliciting proposals for concept studies for SPICA instrumentation which will be funded in FY 2010. The schedule is shown in Figure 13, and the key phase durations and dates are shown in Tables 7, 8.

Table 8: BLISS for SPICA: Key Event Dates

Project Milestone	**Date**
Start of phase A	Sept 2010
Start of phase B	Sept 2011
Preliminary design review (PDR)	Oct 2012
Critical design review (CDR) (includes BLISS instrument integration review)	March 2014
Pre-ship review for BLISS	June 2015
Delivery of BLISS to JAXA	Oct 2015
System integration review (SPICA)	Nov 2016
Launch readiness date	Oct 2017
End of mission—primary	June 2023
End of mission—extended	TBD

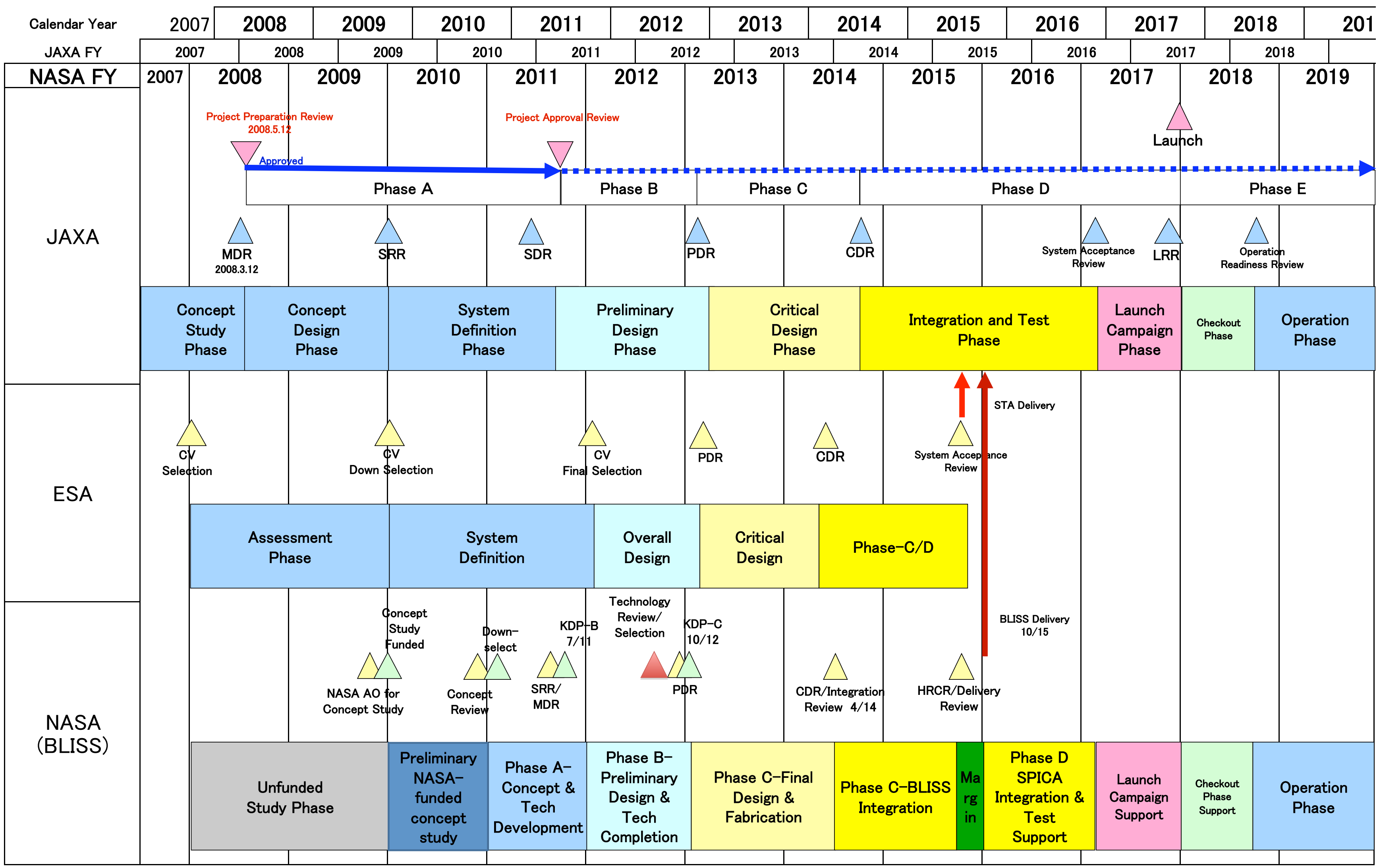


Figure 13: SPICA schedule (build phase), showing key dates for JAXA and ESA, and our approach for BLISS. Note that the JAXA fiscal year is 6 months out of phase with the NASA fiscal year. Phase E extends for 5 years, to 2023.

7 Cost Estimate

The anticipated total cost to NASA for SPICA participation would include both the hardware development and integration, but also support for data processing and archiving and direct grants to the US scientific community to make use of SPICA data after launch. The cost for the BLISS instrument as currently envisioned is well-estimated. The cost of the data support, archiving, and community support is less well-constrained, as it will depend on the US allocation of observing time and SPICA's instrument configuration, details which would be worked out once the US participation is initiated. We anticipate that it will be comparable to the US participation in Herschel. We do not present a detailed costing of this US user support here, but refer the reviewer to the original BLISS submission on the web page.[‡‡]. We note that the bulk of the US user support we envision (not shown in Figures 14 and 15 and Table 7.4) will occur outside the 2010–2020 decade.

7.1 BLISS Instrument Cost

The cost estimates summarized in this document were generated as part of a Pre-Phase-A preliminary concept study, are model-based, and do not constitute an implementation-cost commitment on the part of JPL or Caltech. The accuracy of the cost estimate is commensurate with the level of understanding of the mission concept, typically Pre-Phase A, and should be viewed as indicative rather than predictive.

To estimate the cost of a BLISS instrument, the JPL Team X group has worked with the scientific / technical study team to consider the necessary development, the design and fabrication of all the subsystems, as well as integration, test, delivery to JAXA, and support after launch. The figures include the estimated cost of technology maturation in the first 24 to 30 months to optimize the instrument performance. The Team-X estimated total cost to NASA to build, integrate, and support the BLISS instrument is \$115 M, not including reserves. This includes just over \$10M for the instrument science team, most of which will be in Phase E. With reserves the total estimate is \$148 M. The breakdown is provided in Table 9, and the profile in Table 7.4, with detailed assumptions following. The NICM model for BLISS, and the adjustments to that model are presented in Figures 16 and 17.

7.2 Costing Assumptions for the BLISS Instrument Hardware and Integration

- BLISS is 10 individual spectrometer modules operating in 5 wavelength bands which combine to cover the full 38–430 μm waveband (see Table 2). Each band has a pair of spectrometers A and B, arranged so that the five bands of the A bank couple to the same sky position, providing full simultaneous wavelength coverage, and the five bands of the B bank couple to a second sky position. A cryogenic chopping mirror exchanges the source from the A bank to the B bank as in the single observing mode. The resolving power is R$\sim$700.

[‡‡] `http://www.submm.caltech.edu/BLISS/decadal/BLISS_decadal_final.pdf`

Table 9: BLISS Instrument Cost Estimate from JPL Team X

Item	Cost FY09 $M
Optics	6.9
Structures	10.9
Thermal Systems	9.0
Detectors and Cold Electronics	32.3
Warm Electronics	14.0
Software	1.1
Management, Sys. Eng., and Mission Assurance, ITAR compliance	17.6
Integration and Test	7.4
Science Team in Phases B, C, D (1.5 FTE, 5.5 years)	3.2
Assembly, Test, and Launch Operations (3 FTE, 1.5 years)	1.5
Instrument team science in Phase E (5 FTE, 5 years)	7.5
Ground Data System	3.6
Total without reserves (and w/o FY10 concept study)	**115**
Reserves (30% in Phases A-D)	31.5
Reserves (15% in Phase E)	1.5
Total including reserves (no FY10 concept study)	**148**

- Mechanically, BLISS mounts to the 4.5 K SPICA instrument interface, but there is an additional thermal interface with the SPICA 1.7 K cooler.
- All spectrometers and the detectors are cooled to 50 mK with a custom magnetic refrigerator, built as part of the instrument.
- A thermal intercept at a temperature of 0.4–0.5 K is employed to for a reduce the parasitic loads (conducted and radiated) on the instrument
- The detectors are absorber-coupled transition-edge superconducting bolometers (TESes), of which there are 4224 in total. They are read out with a superconducting 50 mK multiplexer using a time-domain row-column switched readout.
- Three or perhaps for mirrors are required for relaying the beam from the telescope focal plane to the instrument, these are mounted to a 4 K stage. One is a chopping mirror which modulates the light from an astronomical source between the two spectrometer banks.
- Development in advance of the flight engineering is included for the detectors and their readout systems.
- SPICA will launch in 2017 to L2, Phase-E instrument-team science costs are based on a 5-year scientific lifetime.

7.3 Responses to Cost Questions

1. *Provide manpower estimates and cost by year/Phase for all expected scientists that*

will be involved in the mission. All of our scientist labor is included in the costing. We have budgeted a total of 8.25 FTEs for scientist labor in phases A–D (costing \$3.2M), expended uniformly through this period at \$0.5M per year for just over 6 years. We then include a total of 25 FTEs for science in phase E (costing \$7.5M), burned uniformly over the 5-year lifetime of the mission.

2. *If ESA or another key partner is assumed to be a partner or a major contributor, provide an estimate by year and Phase for the breakdown between NASA and ESA (or other) contributions.* Not applicable to the BLISS cost.

3. *Provide a description and cost of what will be performed during Phase A by year. Also include total length of Phase A in months and total Phase A estimated costs.* Our program must ramp up quickly to maintain the SPICA schedule. Phase-A is planned to be 12 months and cost \$12M (including reserve). It is the beginning of the technology maturation period (phases A and B), and will consist process development for the detectors & cold electronics, as well as the cryogenic system but also system engineering and interface definition Specifically:

   Detectors & Cold Electronics. The detector budget of \$4.2M consists of

   - Procurement of two closed-cycle dilution refrigerators, including the associated pulse-tube coolers, cryostats, and mounting hardware, and multi-channel electronics: 2 × \$580k = \$1.2M
   - Maturation of the transition-edge sensors (TES) material process, consisting of either improved yield in the Mo-Au bi-layer film design, or switching to an Ir-Pt alloy bulk material: 4 FTEs + microdevices lab fees and equipment = \$1.2 M
   - Maturation of the detector / backshort integration using double-silicon-on-insulator wafers and XeF2-based surface micromachining (see Figure 9): 3 FTE + microdevices lab fees and equipment = \$0.9 M.
   - Integration of the detectors with the readouts: the multiplexer Nyquist chips, SQUID series array chips, and bias filters in a single package: 3 FTEs + MDL fees and equipment: \$0.9 M

   Sub-K Refrigerator. Phase A includes \$1.1M for development of the 50 mK refrigerator system – this will support be 3 FTEs + equipment and cryogen charges split evenly between 3 tasks: salt pill construction, 50 mK heat switch construction, and continuous system testbed assembly and demonstration.

   Structures. \$1.8M is included for structures – this will support the instrument thermal & mechanical design effort which is required early on to provide constraints on the interfaces with the spacecraft. The WaFIRS and echelle spectrometers have well-constrained sizes based on the existing optical designs, but their masses and mechanical support systems will require early engineering. This work element also includes a detailed study of the magnetic shielding required for BLISS, since it may be an important mass contribution for BLISS.

Optics. We plan 2 FTEs for optics design: one for detailed designs of the foreoptics (relay mirrors, chopper and dichroic/polarizing spiltter network), and one for detailed design of the spectrometer modules themselves.

Systems Engineering and Interface Definition. Finally, Phase A also includes \$2.2M for (non mechanical) systems engineering (2.5 FTEs) and interface definition with the SPICA team (2.5 FTEs) (including mechanical, thermal, optical, electronic, and data). The element also includes setting up technology authorization agreements (TAAs) to insure ITAR compliance throughout the program (1 FTE).

4. *Fill out the Mission Cost Funding Profile Table.* See Table 7.4.

5. *For those partnering with ESA, JAXA, or other organizations, provide a second Mission Cost Funding Profile table and indicate the total mission costs clearly indicating the assumed NASA and contributed costs.* Not applicable for the BLISS build.

7.4 Cost Figures and Tables

Cost figures and tables appear on the following pages.

Table 10: BLISS Cost Funding Profile

Cost $M RY	NASA Fiscal Year 20XX									Totals	
Item	10	11	12	13	14	15	16	17	18-22	RY$	FY09$
Concept Study	0.25									0.25	0.25
Optics		0.6	1.4	1.5	1.5	1.6	0.8	0.9		8.2	6.9
Structures		1.8	3.9	4.1	2.6					12.3	10.9
Thermal Systems		1.1	1.4	1.7	1.8	1.8	1.4	1.5		10.7	9.0
Detectors & Cold Electronics		4.2	5.7	6.8	7.0	7.3	3.5	3.6		38.1	32.3
Warm Electronics			1.7	3.4	4.3	4.0	1.7	1.8		16.8	14.0
Software				0.3	0.5	0.5				1.3	1.1
Mgmt., Sys. Eng., Mission Assurance, ITAR compliance		2.1	2.2	3.0	3.1	3.2	3.3	3.4	5×0.22	21.3	17.6
Integration & Test					1.5	3.0	3.1	1.6		9.3	7.4
Science Team A–D		0.1	0.6	0.6	0.6	0.6	0.7	0.7		3.9	3.2
Assembly, Test and Launch Ops							1.0	1.0		1.9	1.5
Instrument Team Science in E									5×2.2	11.0	7.5
Ground Data System				0.4	0.4	0.4	0.4	0.4	5×0.53	4.8	3.6
Total w/o Reserves	0.25	9.8	16.8	21.7	23.3	22.5	16.0	14.9	5×2.9	**139.8**	**115.3**
Reserves (30% in A–D)		2.9	5.1	6.5	7.0	6.7	4.8	4.5		37.5	31.5
Reserves (15% in E)									5×0.44	2.2	1.5
Total RY$	0.25	12.7	21.9	28.2	30.2	29.2	20.7	19.4	5×3.4	**179.5**	
Total FY09$	0.25	11.9	19.8	24.6	25.5	23.8	16.3	14.7	5×2.3		**148.2**

Note: Annual inflation of 3.5% is assumed in converting between $RY and $FY2009.

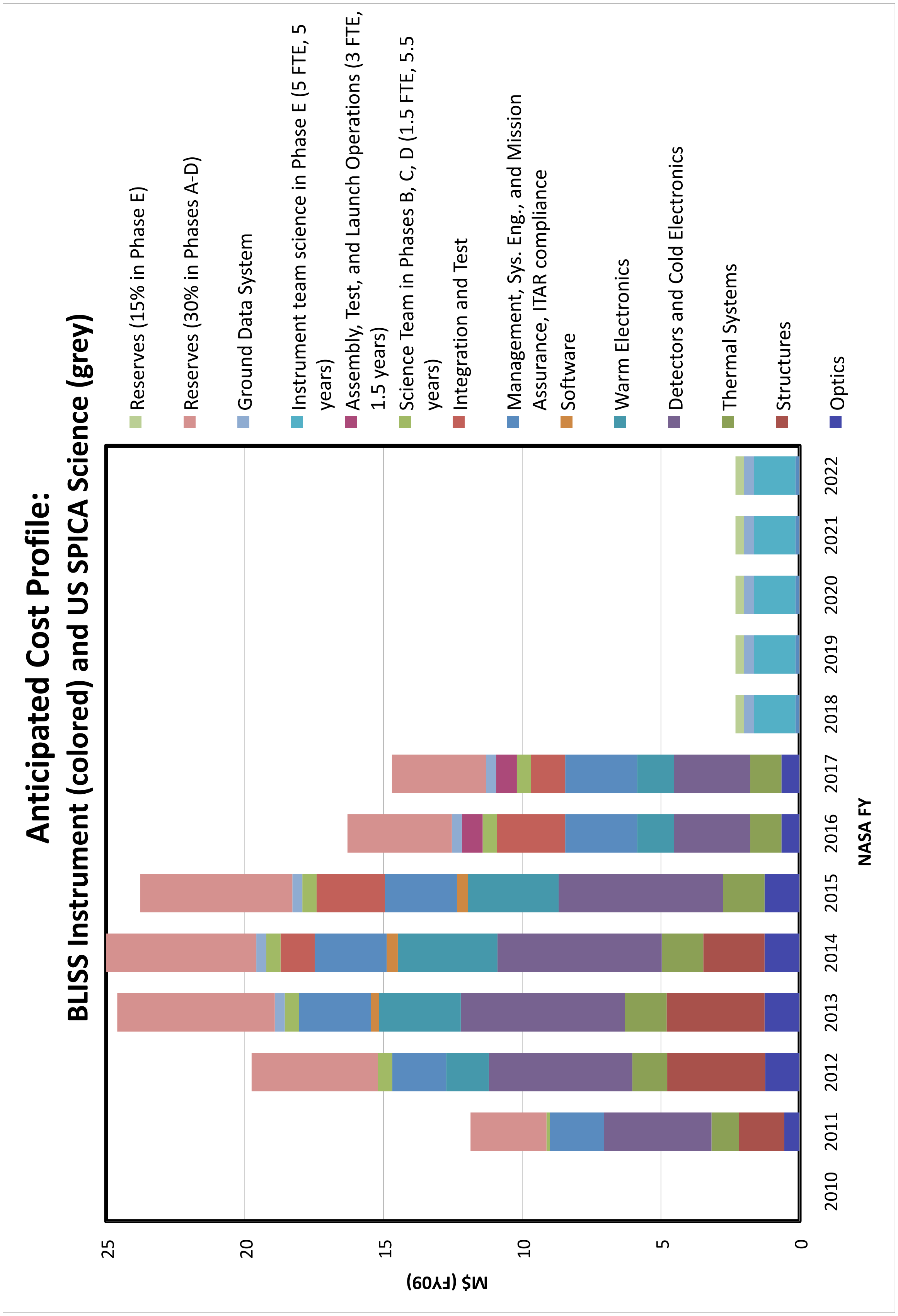


Figure 14: Anticipated cost profile for BLISS hardware build, integration with SPICA, and instrument team science. Annual inflation of 3.5% has been assumed in converting between $RY and $FY2009.

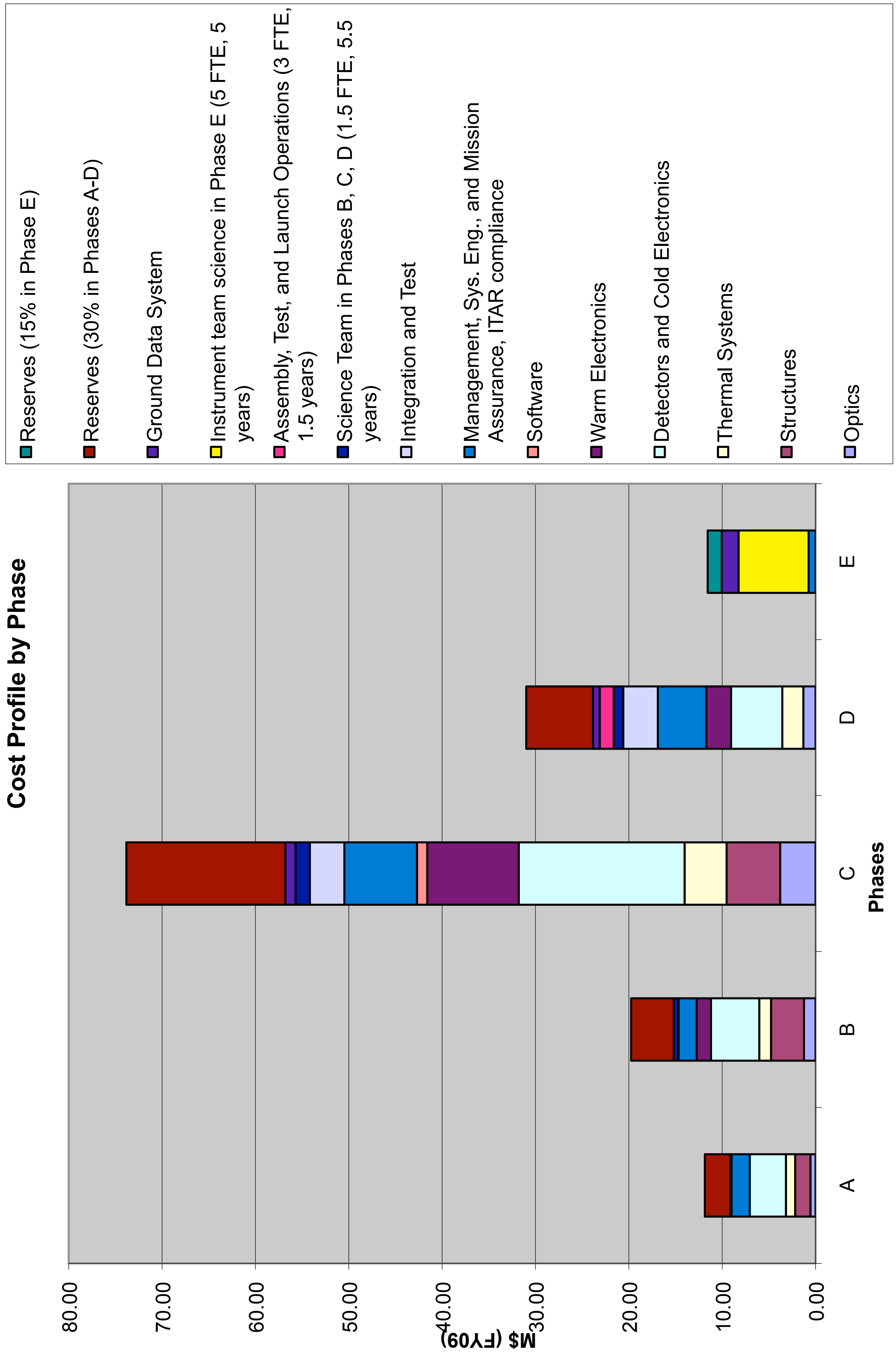


Figure 15: Anticipated cost profile with program phase for BLISS hardware build, integration with SPICA, and instrument team science.

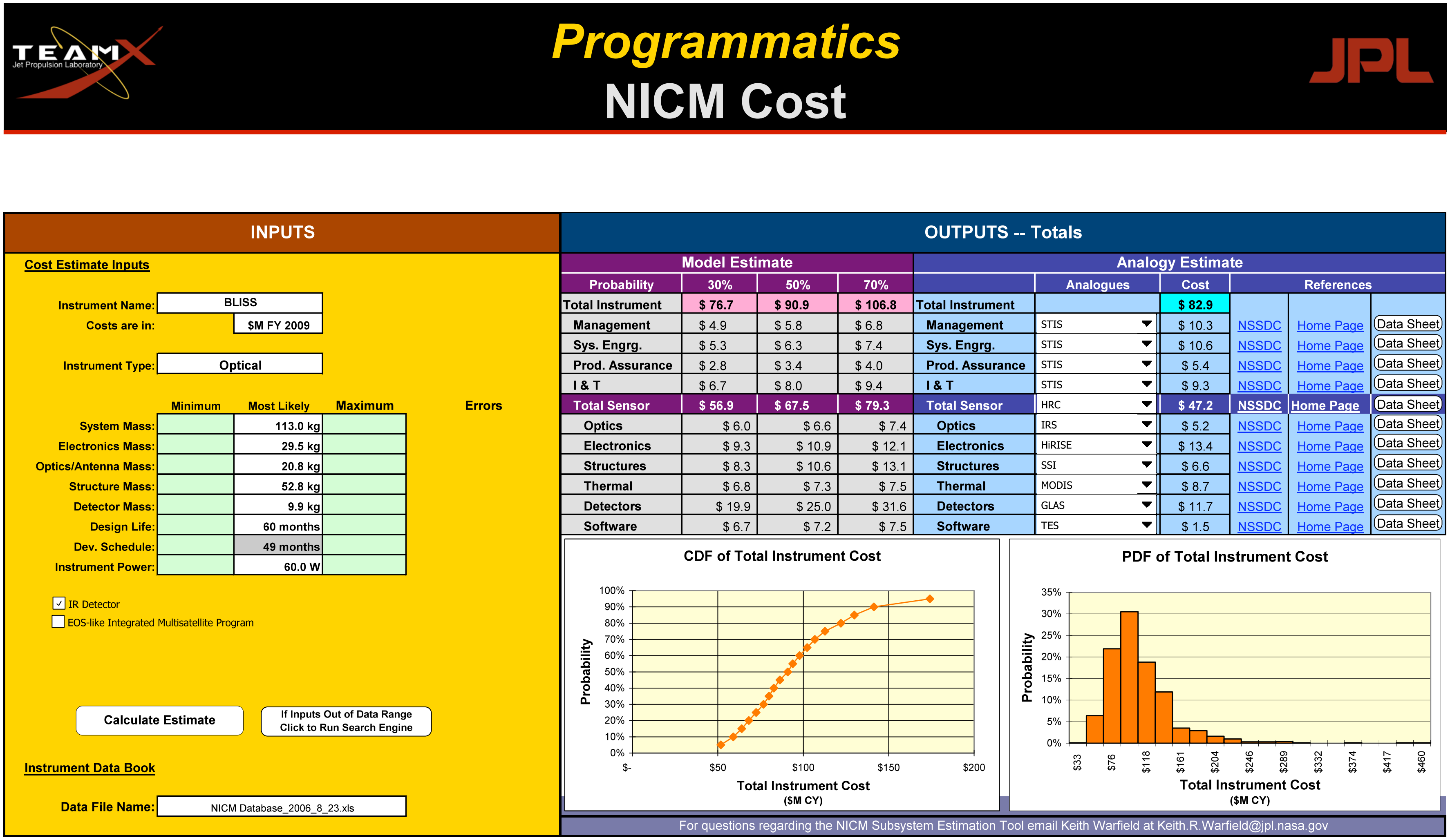


Figure 16: NICM cost model for BLISS instrument.

Model Estimate								
	NICM			Tech Dev (3 year)		Non-Instrument		Summary
	NICM	Adjusted	Rationale	Adjusted	Rationale	Adjusted	Rationale	Adjusted
Total Instrument	**$ 90.9**	**$ 84.1**		**$ 14.0**		**$ 16.7**		**$ 114.7**
Management	$ 5.8	$ 5.4		$ 1.0				$ 6.4
Sys. Engrg.	$ 6.3	$ 5.8		$ 0.8	1 FTE (3 yrs) define interfaces			$ 6.6
Prod. Assurance	$ 3.4	$ 3.1						$ 3.1
I & T	$ 8.0	$ 7.4						$ 7.4
Total Sensor	**$ 67.5**	**$ 62.4**		**$ 11.8**				**$ 74.2**
Optics	$ 6.6	$ 6.9						$ 6.9
Warm Electronics	$ 10.9	$ 11.0		$ 3.0	Flt Ready & Low Power			$ 14.0
Structures	$ 10.6	$ 10.9						$ 10.9
Thermal	$ 7.3	$ 7.5		$ 1.5	ADR Dev., Fac. & Components			$ 9.0
Detectors & Cold Electronics	$ 25.0	$ 25.0		$ 7.3	FTE's, MDL Fees, etc for Dev			$ 32.3
Software	$ 7.2	$ 1.1	Heritage					$ 1.1
Non-Instrument Costs				**$ 0.5**		**$ 16.7**		**$ 17.2**
Science Team in A,B,C,D				$ 0.5	.5 FTE's (3 yrs)	$ 2.7	1.5 FTE's (5.5 yrs)	$ 3.2
ATLO						$ 1.5	3 FTE's (1.5 yrs)	$ 1.5
Science Team E						$ 7.5	5 FTE's (5 yrs)	$ 7.5
Data System						$ 3.6		$ 3.6
ITAR Compliance						$ 1.1		$ 1.1
TAA's						$ 0.3		$ 0.3

Figure 17: Cost adjustments to NICM model for BLISS. All figures are in FY 2009 \$. The software costs are reduced relative to NICM given the simplicity of the observing mode. A technology development effort is included in order to optimize the instrument performance in advance of the flight build. An additional \$16.7M is included for instrument-team science and systems engineering.

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