8 Strawman Program: ALMA Development

The ALMA Development program is an IA function described in the AOP. The funding line is carried in the guideline budget, and only this one budget line is discussed here.

In this section we outline a strawman development program for ALMA over the timeframe of this proposal, appropriate in scope to the NA ALMA Development funding line. This is intended only as indicative of the potential for ALMA development programs, including cost estimates. The ALMA Project will issue a call for proposals to the international community for actual development efforts, and the plan presented below is not meant to preempt the result of that process.

For the strawman plan, we select those projects identified by the ALMA North American Science Advisory Committee (ANASAC) as having the highest scientific potential that also have a significant North American work component. The selected projects fit within the funding envelope for the North American share of the ALMA development line presented in the AOP.

Table 8-1: Strawman Work elements for ALMA Development program

ALMA Development Program PROJECT CATEGORY	PROJECT
New Capabilities	
	VLBI
	Band 1
	SIS mixer Development for Band 11
Programs for increased efficiency	
	Upgrading Band 9 to a sideband-separating receiver
	Improving Band 3 efficiency by 25%
	Widening the IF bandwidth of Band 6
	Support for sub-arrays
	Increased data rate

8.1 Overview

When ALMA commences a program of Early Science in 2011, it will already have surpassed any other millimeter facility in sensitivity and resolution, and by nearly two orders of magnitude at submillimeter wavelengths With the expected impact of these Early Science observations, ALMA's ability to drive and transform astronomical research will be well established by the time it reaches full operation in 2013. Having invested ~$1.3B to realize the biggest advance ever in ground-based astronomy, the astronomical community need to keep the facility upgraded to maintain and expand its capabilities. The ALMA Operations Plan envisaged an ongoing program of development and upgrade. ALMA's design (Wootten and Thompson 2009) allows for expansion of the 50 antennas in the 12m Array to a complement of 64. ALMA will operate from 3mm to 0.3mm across a decade of nearly complete frequency access broken only by the atmospheric limitations of its spectacular site. ALMA's wavelength coverage can potentially be extended by another 50% to cover 1 cm to 200 microns, bringing additional key astronomical phenomena into its grasp. With a modest investment of less than 1 percent of capital cost per year divided among the three funding entities, ALMA will continue to lead astronomical research through the 2010 decade and beyond.

The astronomical community has identified several scientifically compelling programs to spearhead the North American strawman development plan. Many of these programmatic items take advantage of recent technical advances, an example of which is increasing the 3mm sensitivity by refurbishment with MMIC amplifiers. Others, such as building sensitive receivers at the highest frequencies, will require development during the coming decade as detailed in the recent Astro 2010 Decadal Survey White Paper on technology development for terahertz frequencies. In the following subsections, we provide scientific motivation for a suite of key science goals driving the various possible development projects, along with technical details and estimated budget.

ALMA development projects fall into two broad categories: adding new capabilities, and maintaining and increasing the efficiency of existing capabilities. The productivity of the observatory ultimately depends on both of these activities, which are discussed in turn.

8.2 New Capabilities

8.2.1 VLBI

The ALMA construction project does not include funding for the hardware and software required to support VLBI observations with the phased 12m array. The ALMA Board has agreed that phasing-up ALMA will be an extremely valuable enhancement to the telescope and that it will make possible some unique scientific projects. Perhaps the most compelling case for VLBI with ALMA is to image the gravitational shadow of the event horizon of the black hole at the Galactic Center. This experiment requires the high sensitivity of ALMA in combination with (at least) several other millimeter telescopes scattered across the world, a future network termed the Event Horizon Telescope (EHT). The observation cannot be performed at frequencies below 200 GHz primarily due to interstellar scattering effects, but also due to insufficient angular resolution even with the longest intercontinental baselines.

The challenge of VLBI at high frequency is to obtain phase-coherent data in the face of rapid atmospheric changes at each site. With the large collecting area of ALMA, fringe-fitting can be performed on a timescale shorter than most atmospheric changes, thus enabling the time-dependent phase of each VLBI antenna to be measured. This measurement allows the effective use of all of the baselines between the smaller VLBI telescopes. Another exciting VLBI project that would benefit from ALMA in the same way is to image the launch region of AGN jets at 86 GHz and above. The enormous power of AGN jets provides an important role in galaxy evolution but our knowledge of the physics of jet formation has been elusive in the absence of higher resolution observations.

Most of the firmware to form the coherent sums over the array (up to 64 antennas) is already built into the bilateral ALMA correlator. The major missing hardware components include a hydrogen maser, a digital backend to process the correlator output and prepare it for the data recorder. Significant personnel effort from key members of the control software team will be needed to interface the new hardware components and implement the phasing algorithm. The list of software modifications and additions has been delineated in detail in the EHT proposal. The total budget has been developed in consultation between NRAO and EHT, and is $4.9M, phased as shown in Figure 8-1.

8.2.2 Band 1 (7-10mm)

Recent international workshops on the future prospects of Q-band (31-50 GHz) observations have provided a compelling case for the addition of Band 1 to ALMA. ALMA complements the northern hemisphere EVLA by providing better sensitivity to broadly distributed signals owing to its larger beam and more efficient antennas. This band would provide the best platform for high angular resolution cosmological studies utilizing the Sunyaev-Zeldovich effect. It also contains numerous transitions from warm molecular gas in high redshift galaxies, including CO(3-2) at z=6-10. For Galactic work, it allows one to probe the long wavelength emission from dust grains, including large grains in protoplanetary disks. This emission will remain optically thin even in the highest column density structures, allowing the detection of molecular lines in the innermost regions of protostellar disks and AGN. The 7mm band contains many of the strongest emission lines from both light abundant molecules with widespread emission, such as CS, H_2CO and CS, and heavy organic species such as glycine, prebiotic molecules that may play a role in the inception of life. Strongest emission from carbon chain molecules, including the recently identified anions, occurs in the 7mm band for moderate density and temperature.

The development funds should be used to build and test a prototype Band 1 cartridge, including testing at the AOS in a production front end in FY2014. After the successful demonstration of a prototype, production can begin on the remaining full suite of band 1 cartridges. It is assumed that the second band 6 test set can be modified for band 1 use (a larger test dewar is needed though, since the band 1 cartridge diameter is larger). Delivery of production band 1 cartridges would begin in FY2015. The proposed budget of $3.92M allows for the first five WCA and CCA pairs to be delivered by the end of FY2015.

8.2.3 SIS mixer development for Band 11 (250μm)

The key component in any astronomical instrument is the detector. During the past 25 years, the revolution in millimeter and submillimeter astronomy has been enabled in large part by the ongoing development of sensitive heterodyne mixer receivers employing superconductor-insulator-superconductor (SIS) tunnel junctions. Research in superconducting materials and mixer design has led from the early lead alloy junctions with modest performance (by today's standards) to modern niobium-based junctions with sensitivities better than ten times the photon noise limit in all of the ALMA bands. By the time it enters full operations, ALMA will be the largest assembly of SIS mixers with over 1000 devices deployed at any time. Future procurement of mixers will be needed to maintain and repair all of the bands, including Bands 3 and 6, which are North American deliverables. As the observatory matures, there will be strong scientific motivations to upgrade the sensitivity of one or more receiver bands, or add a new band. Already, we can see the potential of the next higher frequency band "Band 11."

Although the highest frequency band originally planned for ALMA reaches only up to 950 GHz, observations with ISO and APEX have demonstrated the scientific importance of the terahertz band. Due to the high elevation, the ALMA site provides sufficient atmospheric transparency (over 30%) in a few windows from 1.0-1.6 THz that it is worthwhile to consider adding capability to exploit them. For example, ISO's detection of strong, high-J rotational transitions of CO revealed a component of hot gas (1000K) seen toward young low-mass protostars like L1448. High spectral resolution observations of these lines provide a simple way to measure the column density of hot gas in a variety of objects (shocks, hot IAs, PDRs) with no interference from cool foreground gas as is often the case in lower transitions.

Observations of other molecular species in this hot gas will reveal the chemistry in a temperature regime previously accessible only to ISO. The terahertz band contains unique spectral features such as the fundamental rotational transitions of NH+ and para-H2D+. The chemistry of nitrogen in the ISM is not well understood. Observations of NH+ will provide important insight into the formation of N2H+ and NH3. Although the ortho form of H2D+ has recently been detected in several sources at 372 GHz, in the cold temperatures of the ISM, para-H2D+ is thought to be the dominant form. As a deuterated molecule that remains in the gas phase longest, H2D+ is one of the few ions or molecules that can probe the midplane of protostellar disks.

The terahertz band also provides access to the J=3(0)-2(0) transition of LiH at 1.329 THz. The two lower transitions are both at more opaque frequencies of the atmosphere. Currently the abundance of LiH in the ISM is unknown and a detection of this transition would be an important step in understanding the chemistry resulting in LiH formation. In the future observations of LiH as a function of redshift will make it possible to derive the true lithium abundance (Combes and Wiklind 1998).

The brightest emission line in the spectrum of most galaxies is the 157μm [C II] line. Although the [C II] line does not enter 'Band 11' for redshifts below about z~0.2, its strength provides an important diagnostic of atomic gas in galaxies. At present, the line must be observed from above the atmosphere, a locations where collecting area is limited. The line is a prime target for the Herschel spacecraft. ALMA's sensitivity and resolution would provide important keys to understanding the gas giving rise to the line. Although somewhat weaker, the 205 μm [N II] line occurs in this window. It is among the brightest emission lines in galaxies, tracing higher excitation conditions than the [C II] line. The line has been observed in galactic sources from single antennas on high Chilean sites.

Fabrication of SIS mixer chips requires significant infrastructure to execute the material sputtering and wafer etching processes in combination with an experienced research staff. As a result, there exist only a few laboratories around the world that can produce SIS mixers with state-of-the-art sensitivity. In the United States, the two producers of SIS mixer chips are the University of Virginia's Microelectronics Lab (UVML) and Jet Propulsion Laboratory's (JPL) Microdevices Lab. Much of the recent SIS work at JPL had been to support the receivers on the Herschel Observatory and the Scanning Microwave Limb Sounder. The level of future activity on SIS devices at this lab is uncertain due to NASA's need for other kinds of microdevices for various future missions. The UVML represents a capital investment of order $10M in research and test equipment plus many years of labor investment to establish and maintain a working facility and a stable SIS mixer fabrication process.

The international ALMA project has recognized that ALMA Operations must support continuing R&D for SIS mixers. Because of its importance, the previous NAASC proposal included funds to support the UVML group through a subcontract to develop Nb/Al-AlN/NbTiN SIS junctions, even as they deliver the final production Nb/AlOx/Nb devices to the ALMA Band 3 and Band 6 cartridge manufacturers, but this contract expires after 2012 and can no longer be supported as an operations activity. In the strawman development plan we suggest that the ALMA development program be used to extend this support to enable work to develop a sensitive mixer for Band 11.

8.2.4 Cartridges for Band 5 (1.6mm)

ALMA Band 5 covers the range 163–211 GHz (1.8–1.3 mm), which includes the strong atmospheric water absorption line at 183 GHz and its wings. Under excellent conditions at Chajnantor, the opacity in this line may go below unity, allowing observations of the line outside the atmosphere in astronomical sources. Band 5 will also be important for red-shifted [C II] lines in the range z =8-11. Moreover, it covers the H_2O 183 GHz and the H_2O line at 203 GHz. The 183 GHz line is a strong maser, but can also probe extended thermal emission under exceptional conditions. The 203 GHz line offers a unique possibility to image an optically thin isotopic water line from the ground at high angular resolution. Such studies would be important complements to others carried out with the Herschel Space Observatory at lower angular resolution in the same timeframe. It is a crucial band to measure CO, [C II] and dust in critical redshift ranges and provides important opportunities for astrochemistry.

Six Band 5 cartridges will be produced through an EU contract from funding additional to ALMA construction. As a result, development funding will not be required. Since Band 5 was a European deliverable, it is assumed that European sources of funding would be used to perform this upgrade, and it is not included in the funding total for the North American strawman plan.

8.3 Programs for Increased efficiency

8.3.1 Upgrading Band 9 (450μm) to a Sideband-Separating Receiver

The highest frequency bands of ALMA will be attractive to observers for many reasons: the dust emission becomes brighter, the spectral lines typically arise from gas at higher temperatures (i.e. closer to the powering sources), and far-infrared cooling lines become accessible at moderate redshifts. Moreover, these bands offer the potential for the highest angular resolution observations possible by ALMA (5-10 milliarcsec). However, even from the excellent high-altitude observing site of ALMA, atmospheric noise imposes a significant limit to the ultimate sensitivity at high submillimeter frequencies. One way to reduce this noise contribution is to employ sideband-separating (2SB) receivers, which reduce the noise contribution from the image sideband by a large factor compared with the simpler design of a double-sideband (DSB) receiver. All ALMA receivers below Band 9 are 2SB, however the current Band 9 receivers are DSB as this configuration was the state-of-the-art at this frequency when production was initiated. Another drawback to the current Band 9 DSB receiver will be encountered in total power (non-interferometric) spectra of line-rich objects, in which every feature will have a sideband ambiguity. This is unfortunate because the highest frequency bands are where the total power spectra will be most necessary as the sources of interest will occupy the largest fraction of the primary beam. Although the upgrade of a 2SB receiver will only mitigate rather than eliminate this problem, it will enable other observational techniques (such as rapid LO offsetting) to effectively eliminate it.

A design study of a 2SB mixer upgrade for Band 9 with minimal impact to the existing receiver was recently published by members of the original Band 9 manufacturing group (Hesper et al. 2009). The hardware requirements are new 4-8 GHz isolators and low noise amplifiers. Other hardware, including the SIS mixers, can be reused. The total cost of such an upgrade has been estimated by the Band 9 group. Since Band 9 was a European deliverable, it is assumed that European sources of funding would be used to perform this upgrade, and it is not included in the funding total for the North American strawman plan.

8.3.2 Improving Band 3 (3mm) sensitivity by 25%

Band 3 plays a very important role for both science and calibration of the higher frequency ALMA bands through the technique of phase transfer. The fundamental point source calibrators for ALMA (quasars) are brighter at lower frequency, and the overall system sensitivity is better there. Therefore, it will often be more efficient to measure the atmospheric and the receiver-independent instrumental gain changes in Band 3 and scale them appropriately into corrections applied in the higher frequency bands. If the sensitivity of Band 3 can be improved, observations in other bands will benefit because the angular separation from the nearest potential calibrator from any given target source would become smaller. This reduction will lead to smaller residual phase errors in the final data product that will provide higher fidelity images. For targets that already have a nearby calibrator, less time would need to be spent on each calibration.

When Band 3 was designed, SIS mixers gave the best performance then available at this frequency. With the recent substantial gains in HEMT technology demonstrated at NRAO, the situation has changed. This development project would demonstrate an integrated HEMT LNA and Schottky sideband-separating balanced mixer that can be a lower-noise drop-in replacement for the current Band 3 SIS mixer. The new HEMT Band 3 LNA should reduce the receiver noise temperature between 3-10K over the band. For Band 3 observations (assuming 75th percentile atmospheric conditions, 60 degree elevation, and 270K mean atmospheric temperature), the sensitivity increases 11-35% for a 3-10K decrease in receiver noise temperature over most of the band. For the 115 GHz CO line, where the atmosphere is considerably more opaque and therefore contributes more to overall system temperature, a 6-20% increase in sensitivity is gained for the same 3-10 K decrease in receiver noise temperature. Compared to the baseline 50 antenna system, a 6-35% sensitivity improvement is equivalent to adding between three and seventeen more 12-meter antennas.

Following the construction of the first units, performance verification at the AOS would occur in FY2013 with production of the replacement LNA-mixer units then beginning in FY2014 and ending in FY2015 for a total cost (M&S plus labor) of $1.5M. The project budget assumes that one of the current Band 3 cartridge test sets can be used for testing of retro-fitted Band 3 cartridges. First retro-fits can be done on spare Band 3 cartridges, then need to refit and test at front end maintenance pace of one per month. In the strawman plan, retro-fitting and re-testing of Band 3 cartridges would begin in late 2014 and finish in 2020 (limited by one-per-month front end maintenance pace).

8.3.3 Widening the IF Bandwidth of Band 6 (1.3mm)

Band 6 is an important band for spectral line work as it is high enough in frequency to include transitions above the ground state from many common tracers of dense gas (e.g. HCN 3-2, CS 5-4), but still low enough in frequency that the confusion from dust optical depth effects is minimal (at least in most objects). The original specification on the Band 6 receiver included an instantaneous IF passband of 4-12 GHz. This configuration would have allowed any two spectral lines within 24 GHz of each other to be observed simultaneously (along with many others, of course). However, problems in producing cold cartridges with such a wide bandwidth that meet all the other stringent performance requirements has caused the specification to be relaxed to 5-10 GHz in order to meet production schedule and budget. Indeed, some of the performance parameters have been further relaxed over the 5-6 GHz IF range to preserve the ability to observe the three most abundant CO isotopologues simultaneously. To allow proper use of the 4-6 GHz part of the band, two major upgrades are required: A redesign of the cold IF amplifier, and a redesign of the mixers to employ a balanced mixer configuration that will eliminate LO sideband noise. All of the cold cartridges in the field will need to be refit with these items. The cost estimate for the design work and new hardware procurement is $1.6M.

8.3.4 Support for subarrays

The number of subarrays is the number of collections of ALMA antennas tuned to discrete frequencies. These subarrays have in common the use of a particular LO reference signal. This signal is developed by the laser synthesizers, so that the number of these laser synthesizers sets the number of frequency subarrays. The Science IPT recommended at least four, a recommendation endorsed by the ASAC and adopted by the project, refined, and incorporated into the ALMA Science Requirements [SCI-90.00.00.00-0390-00] and into the ALMA System Requirements as SCI-420.

Subarrays are needed for, most importantly, the main interferometric subarray performing scheduled scientific experiments. Some antennas will be incompletely instrumented with receivers. A complete set requires one frequency subarray while the remaining antennas must be included within a separate subarray if maximum use of ALMA is to be realized. ALMA's requirement for excellent imaging demands that short-spacing data be included in its datasets. Particularly for time-critical events, this requires a subset of antennas devoted to total power observations. ALMA's enormous collecting area and number of baselines allow simultaneous multifrequency observing with excellent sensitivity and imaging for transient events, such as gamma ray outbursts, cometary ejection events or solar flares, to specify a few science cases. Elsewhere in this document, black hole event horizon imaging employing the breakthrough resolution afforded by a very long baseline array is described; however, for many projects, a small subarray of antennas would be deployed for VLB experiments. Additionally, in normal operations antenna movements may occur several times per week; baseline determination is most effectively performed with a subarray of antennas.

However, during project rebaselining in 2005 the four required laser synthesizers were decreased to two. The Atacama Compact Array uses two laser synthesizers to provide its required two subarrays. Through the use of a switch, four subarrays are available, though the need grew to six with the addition of the ACA. The cost of two additional frequency subarrays is estimated to be $620K, including hardware and manpower to test and install them. The hardware includes two laser synthesizers, two continuously variable RF synthesizers, and their distribution components.

8.3.5 Increased data rate

By providing 8 GHz of bandwidth with (up to) 32768 channels on each of 2016 baselines with a 0.25 second dump time, the ALMA bilateral correlator can produce up to 1 gigabyte/second of raw visibility data. However, the peak data rate supported by the downstream computer hardware is only 60 megabyte/second. Furthermore, initial ALMA operations will attempt to maintain an average data rate of only 6 megabyte/second, in part to limit the rate of growth of the archive to a manageable level with current computing hardware. We must emphasize that spectral line surveys requiring 0.5 km/s resolution will already flirt with the peak rate limit, as they will be limited to 3 second integrations. But the biggest limitation will be in large area spectral line imaging which requires on-the-fly interferometry. Obtaining one degree images of Milky Way GMCs with sub-arcsecond resolution will be a powerful window into the physics of the interstellar medium and a unique capability for ALMA. However, at the current peak data rate, such imaging would be limited to only one or two spectral lines simultaneously. In order to increase the peak data rate to fully capture the correlator output would require three actions: 1) replace many 1 gigabit connections with 10 gigabit; 2) upgrade the network interface card in many control computers; 3) improve the OSF-to-Santiago network link. Assuming the continued growth in computer hardware capability, it makes sense to wait a few years until these capabilities become less expensive. Therefore, we envision starting these improvements toward the end of this proposal period, as shown on the development budget ramp-up figure.

8.4 Summary for Development Programs

By design, all of the proposed projects fit within the North American share of the AOP recommended budget item for ALMA development, with the following cost sharing scenario:

- VLBI cost shared 50%-50% with EU and will be completed by end of 2015
- Band 1 cost covered by NA funds, and the first 5 production cartridges completed by end of 2015. It will be completed in the next development cycle.
- Band 3 upgrade covered by NA funds, and retrofits will begin in 2015 at a rate of 1 per month, and will be completed in the next development cycle
- Band 5 covered by EU funds
- Band 6 development partly deferred and complete in 2016
- Band 9 covered by EU funds
- SIS development for Band 11 covered by NA funds
- Additional subarrays covered by NA funds

8.5 Plausible Implementation Scenario and Budget

Science will benefit from the new equipment deployed on ALMA through expansion of its window on the cosmos to the longest wavelength window at 7mm and through a tremendous increase in resolution, ultimately enabling an array including ALMA to image events at the black hole at the center of the galaxy on a scale of tens of microarcseconds. Sensitivity in existing workhorse bands at 3 and 1.3 mm will be improved through upgrades to the receiver cartridges in those bands. Addition of frequency subarrays will enable multiband observations of short-lived events. Development will begin to explore the potential of implementation of a band in the short submillimeter spectral window.

Staging of the development is limited by the guidance amounts for available funds. In this plan we have included addition of the two additional subarrays, which will prove helpful during commissioning when some antennas will not have a complete complement of receivers and subarrays of antennas may prove useful for verification.

All science committees gave very high ranks to high-resolution, high-sensitivity imaging as provided by a very long baseline capability; therefore this activity begins early in the period and is complete by its end. New receiver bands are expensive and labor-intensive, and so in this strawman the highly ranked 7mm band effort begins early and ramps up until in 2015 a half dozen receivers are available. Development for upgrades for the 3mm and 1.3mm cartridges and development for deep submillimeter efforts continues through the period. By 2015 ALMA will be a mature instrument, and it is judged that at that time its data rate should begin augmentation, an effort beginning the final year covered in this strawman plan.

This plan is illustrative of what might be accomplished. As described in the AOP, the actual development plan would be derived from an open call for proposals to the international community, full vetting by the science advisory committees, and eventual selection by the ALMA Board

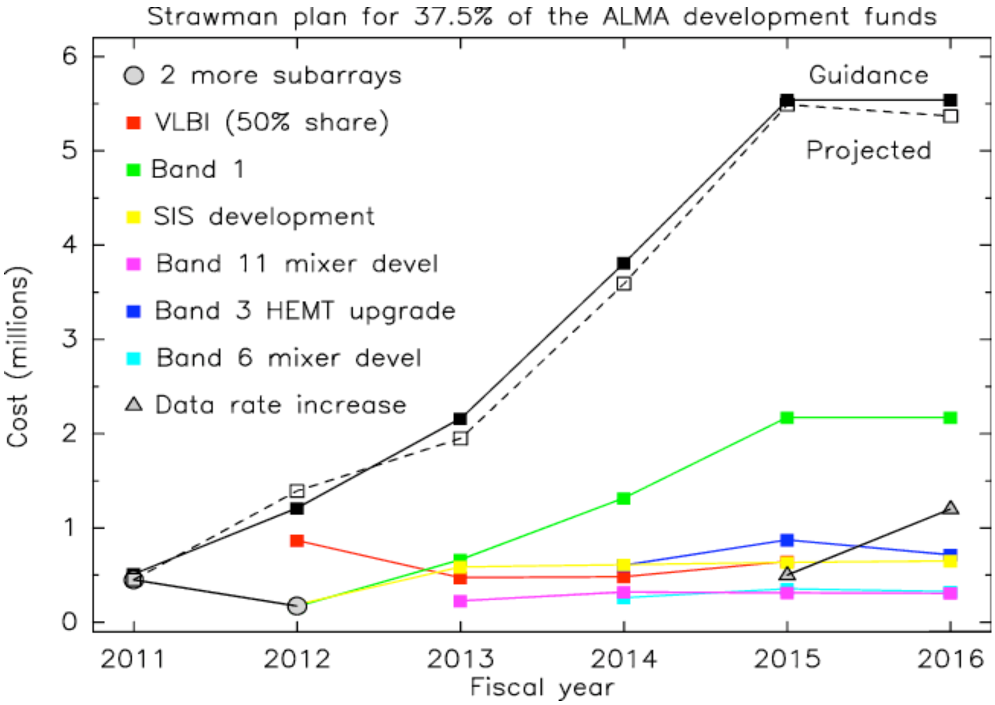

Figure 8-1: Funding profile for Strawman Development Program