Considerations for planning TESS Extended Missions

This document is intended to be a useful reference for those who are planning and proposing for TESS Extended Missions. It is a repository of ideas, questions, and links to relevant work regarding possible Extended Missions. The intention is to capture and organize ideas from the TESS Science Team in order to expedite and facilitate decision-making and proposal writing.

An extended mission offers the chance to re-examine our top-level science priorities, sky scanning pattern, selection of short-cadence target stars, allocation of data volume between "target stars" and full-frame images, and many other mission parameters. Given the broad range of possibilities, we hope to gather input from a broad community of Co-investigators, Collaborators, Working Group members, Guest Investigators, Engineers, and other interested parties.

The Simulations Working Group has prepared a memorandum (Bouma et al.) about 6 specific scenarios for a one-year Extended Mission. The scenarios are:

1. *HEMI*, which re-observes one of the ecliptic hemispheres in essentially the same manner as in the Primary Mission (i.e., neglecting the zone within 6° of the ecliptic);
2. *HEMI+ECL*, which re-observes one of the ecliptic hemispheres, but this time covering the entire hemisphere at the expense of the continuous-viewing zone near the pole;
3. *POLE*, which focuses on one of the two ecliptic poles;
4. *ECL-LONG*, which has a series of pointings with the *long* axis of the field-of-view along the ecliptic (in combination with some fields near the ecliptic pole, when the Earth or Moon would prevent effective observations of the ecliptic);
5. *ECL-SHORT*, which has a series of pointings with the *short* axis of the field-of-view along the ecliptic (again in combination with some fields near the ecliptic pole);
6. *ALLSKY*, which covers nearly the entire sky with 14-day pointings (as opposed to the 28-day pointings of the Primary Mission), by alternating between northern and southern hemispheres.

In what follows, these scenarios are occasionally cited by name. More details on these scenarios and the anticipated planet properties are in the memorandum by Bouma et a. However, the scope of the present document is intended to be much broader, recognizing that there are many other possibilities for scanning the sky, and there are also many other considerations for an Extended Mission beyond the goal of detecting exoplanets.

NEW OPPORTUNITIES FOR EXOPLANETS

More Planets. One may wonder, after the primary mission, will TESS will reach a point of steeply diminishing returns? Based on our simulation results the answer is definitely not. We call attention to one of the more important results of Bouma et al. (Figure 15): there are many transiting planets that will not be detected with data from the Primary Mission, but for which doubling the number of observed transits will enable detection. In other words, the sample of detected planets from the Primary Mission will not be complete, even for short-period planets around the target stars. There may eventually come a point at which the peak of the SNR distribution (shown in Figure 15) will shift past the detection threshold, at which point more observations would only allow us to probe out to longer orbital periods and fainter stars. No study has yet quantified when TESS will reach this point of diminishing returns.

Longer-period Planets. During the Primary Mission, the TESS discovery space is strongly biased toward short orbital periods (tens of days or shorter). By extending the time baseline, we would be able to increase our sensitivity to longer-period planets. This would be of interest in order to

- probe planets that are not strongly affected by stellar irradiation.
- identify potentially habitable planets.

The Extended Mission simulations discusses these issues in detail.

Refinement of transit ephemerides.   For follow-up observations, we will often need to predict future times of transits or occultations, ideally with an accuracy of an hour or less. After enough time has passed that the uncertainty has grown to a significant fraction of the orbital period, we say that the ephemeris has gone "stale," presenting a major obstacle to many follow-up programs. As shown by Bouma et al., Sec. 3.2 (and originally pointed out by P. McCullough), a rough rule of thumb is that for a typical TESS super-Earth, the uncertainty in future transit times (in hours) is comparable to the number of years since the original TESS detection during the Primary Mission. By re-observing these systems during the Extended Mission, we would be able to reduce the uncertainty in future transit times by an order of magnitude (see Fig. 23 of Bouma et al.).

Circumbinary planets. A related issue is the detection of circumbinary planets, which generally have periods longer than tens of days. While it is possible to detect circumbinary planets through multiple transits that take place during a single planetary conjunction, most of the known circumbinary planets have been detected based on data collected over multiple planetary orbits, which requires a long time baseline.

Transit-Timing Variations. An Extended Mission that observes transiting planets that were detected in the primary mission would extend the time baseline of observations, and increase the chance that transit-timing variations (TTVs) can be used to characterize the planetary systems. TTVs can be used to confirm the planet-origin of transit signals, determine the masses and orbital properties of transiting planets (and occasionally non-transiting planets). Many TTV signals have timescales greater than a few years, and the information content typically scales as $t^{5/2}$ (Fabrycky 2013, K2 white paper). The desire to exploit TTVs points toward an Extended Mission that provides:

- Additional coverage of fields that were observed previously by TESS, particularly near the ecliptic poles (the *POLE* scenario), where the Primary Mission provides the longest duration of observations.
- Observations of the Kepler field, in order to provide new transit times for those targets bright enough to be usefully observed by TESS.

NEW OPPORTUNITIES FOR SHORT-CADENCE TARGET SELECTION

Identification of Interesting Variables using the Primary Mission Data. It should be possible to use the data from the Primary Mission to arrive at a very high-value, compelling list of short-cadence targets for the Extended Mission. As currently envisioned, the short-cadence target stars for the Primary Mission will be selected mainly on the basis of transiting-planet detectability, and as such will concentrate on F-M dwarfs. However, the data collected from the Primary Mission should allow for much more powerful and interesting selections of short-cadence targets for the Extended Mission. In particular, the Primary Mission full-frame images can be used to identify many thousands of transiting/eclipsing candidates. These stars could then be observed with a shorter cadence during the Extended Mission to improve the signal-to-noise ratio, refine transit parameters, and search for additional eclipsing objects with longer orbital periods.

The full-frame images from the Primary Mission could also be used to identify large-radius stars on the basis of photometric variability. Such stars can be excluded, if desired, from the short-cadence target list of the Extended Mission, since they are not favorable for planet searching.

More generally, the FFI data from the Primary Mission could be used to identify all the photometrically variable objects; those for which our understanding would benefit from better time sampling could be added to the short-cadence target list of the Extended Mission.

Opportunity to Broaden the Planet Search to Different Stellar Types. After having performed a search of F-M dwarfs during the Primary Mission, we could choose to populate the short-cadence target list with a broader range of stellar types. They would be selected because we want to probe the planet populations around relatively unexplored types of stars, even if those stars are not optimal for planet detection. For example we could choose to target

- cluster members,
- evolved stars (for which it might often be possible to detect asteroseismic oscillations),
- white dwarfs (for which fine time sampling is especially important due to the short eclipse durations),
- massive stars (spectral types OBA),
- very low-mass stars (spectral types LT),
- eclipsing binaries and other multiple-star systems,
- stars for which asteroseismology is feasible and interesting, even if they are not good planet-search targets

For all of these tasks, the basic consideration in planning an Extended Mission is the trade-off of sky coverage versus the duration of observations. For targeting rare and widely dispersed objects, greater sky coverage is favored, while for some applications such as asteroseismology, longer durations are favored.

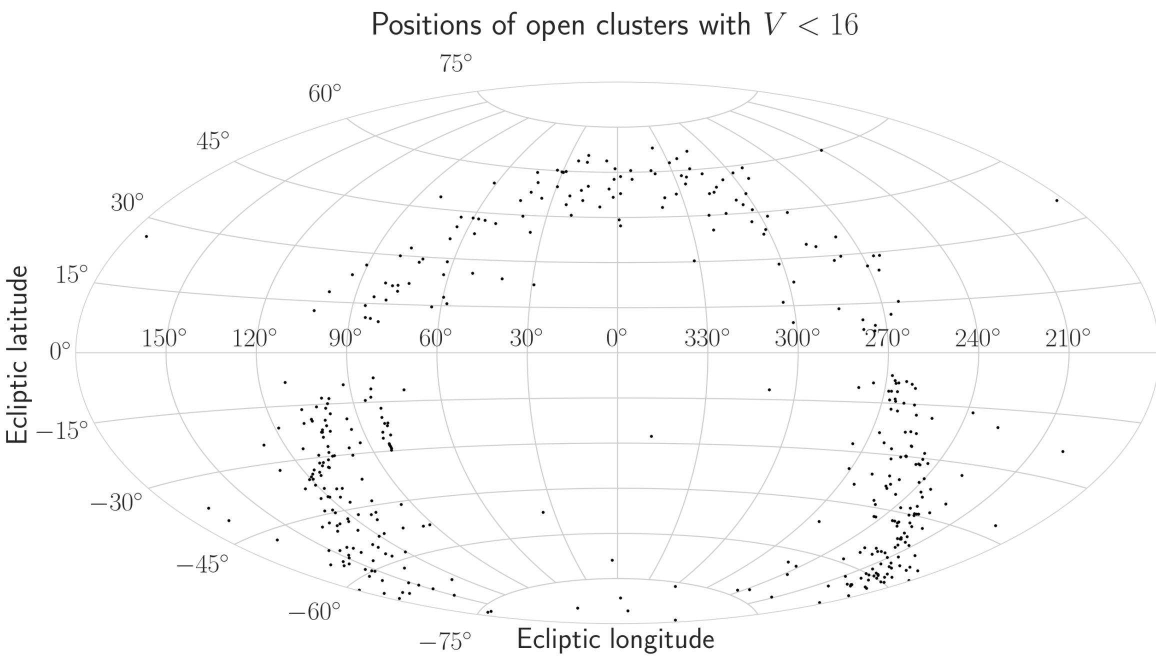
ROTATION PERIODS

Measuring stellar rotation periods is interesting for calibration and interpretation of "gyrochronology". For stars with exoplanets, the rotation period sometimes gives clues about the history of tidal evolution. For Kepler, the measurement of rotation periods for vast numbers of stars led to a number of interesting results. One was the apparent lack of close-in planets around rapidly rotating stars. Another was the apparent bimodality in the rotation period distribution of M dwarfs. Yet another was the demonstration that Kepler planet-hosting stars tend to have low obliquities, based on the distribution of the amplitudes of photometric variability associated with rotation. However, measuring stellar rotation periods will be difficult during the Primary Mission because the typical observation duration of 1-2 months is not long enough for a secure result. Many stars have rotation periods longer than 10 days.

For the most secure measurements of rotation periods, we would want an Extended Mission with longer time coverage of as wide a field as possible, such as *POLE*.

OPEN CLUSTERS

Finding planets in open clusters is interesting because clusters have well-determined ages, and are younger than most field stars. Based on the database on the open cluster survey page, the majority of suitable open clusters with V<16 are near the galactic disk, and they are more common in the southern ecliptic hemisphere (with a south:north ratio of ~2:1). Consequently, for the specific purpose of examining open clusters, it would be advantageous for an Extended Mission to re-observe the southern ecliptic hemisphere. A sky map of these clusters is shown below:



TRANSIENTS

By "transients" we mean phenomena such as novae, supernovae, microlensing events, gamma-ray bursts, gravitational-wave bursts, etc. By the time of the Extended Mission it should be clearer whether there are optical transients bright enough for TESS observations to be useful. By then it should also be clearer how rapidly the TESS data can be made available to the relevant scientists. Assuming, as seems likely, that TESS transient observations prove to be useful and interesting, and that the positions of the transients cannot be predicted in advance and occur nearly randomly on the celestial sphere, then the desire to continue this work would favor an Extended Mission with as wide a sky coverage as possible (e.g., HEMI+ECL or ALLSKY).

Any of the proposed extended mission pointing strategies would enable a SNe Ia search, although they would need to be coupled with ground-based follow-up given the $\gtrsim 1$ month timescales of SNe. For purposes of observing variable stars, the same claim holds: any proposed pointing strategy would work. In all cases, we also note the `quality vs. quantity' trade-off: if the stars in a field are observed for longer (as in *npole*), the light curves of any given star of interest will have more information in them. However, there will be fewer such stars compared to a scenario that covers more sky in a given year, such as *nhemi*. Another practical point is that many of the best-characterized fields for variable-star astronomy, notably the MACHO and OGLE fields, are near the South Ecliptic Pole, which will also have a large overlap with LSST and Gaia.

SOLAR SYSTEM OBJECTS

Szabo et al. have used K2 data to identify main-belt asteroids and measure their rotation periods. Kiss (2016) used K2 light curves to constrain the rotation period and asphericity of Nereid, Neptune's third-largest moon. The desire to perform these types of solar-system projects would favor an Extended Mission with coverage of the ecliptic, particularly for long durations (*ECL-LONG*).

COMPLETING THE ALL-SKY SURVEY

The Primary Mission covers most of the sky, but omits the inner 12° surrounding the ecliptic plane, and also omits selected stripes of ecliptic longitude due to the gaps between observing sectors. One purpose of an Extended Mission could be to complete a truly all-sky survey. To cover the ecliptic, one of the scenarios *HEMI+ECL*, *ECL-LONG* or *ECL-SHORT* could be chosen. To cover the gaps in ecliptic longitude, the *HEMI* or *HEMI+ECL* scenarios are appropriate. The HEMI+ECL scenario could go most of the way to achieving both goals, though it would leave some gaps in the ecliptic plane.

CHOOSING ONE-YEAR PLANS WITH FUTURE YEARS IN MIND

TESS's orbit is stable for more than 1000 years (Gangestad 2013). When planning for any particular year of an Extended Mission, it is worth considering how the program can be complemented or extended by future years of observing, rather than considering each year in complete isolation.

Any of the proposed scenarios could simply be repeated in a subsequent year. A simple point is that the *HEMI*, *POLE*, and *HEMI+ECL* strategies can all be inverted (north to south, or vice versa). Therefore, any of these one-year scenarios are easily doubled to create a two-year mission. By symmetry, the second year would have a similar discovery potential as the first year. If sky coverage is a very high priority, then *ALLSKY* has the advantage of the greatest sky coverage in a single year, as a hedge against mission stoppage in a future year. Furthermore *ALLSKY* can be repeated indefinitely without much modification, which may simplify operations, data handling and other aspects of the mission.

An interesting comparison can be made between one year of *HEMI* in the north and a second year of *HEMI* in the south, versus two years of *ALL SKY*. In the former case, the northern and southern ecliptic caps are each observed for one continuous year. This would allow two-transit detections of planets with orbital periods as long as 6 months. In the latter case, each ecliptic cap is observed for two years, but with a 50% duty cycle (14 days on, and 14 days off). This would allow two-transit detections of planets with orbital periods as long as one year, but with a 50% loss in efficiency due to the duty cycle, and the possibility for period ambiguities.

SHORT-CADENCE TARGET STARS VERSUS FULL-FRAME IMAGES

For the Primary Mission the current plan is to transmit full-frame images (FFIs) with 30-minute time sampling, and the pixel data from immediately surrounding about 200,000 target stars with 2-minute time sampling. (There may be also be a small number of stars observed with even finer time sampling, for asteroseismology.) The allocation of the data volume between the FFIs and target stars need not be the same in the Extended Mission as in the Primary Mission. To our knowledge, no attempt has been made to devise a metric by which the optimal balance between these two types of data can be chosen. As a preliminary calculation, the Simulations WG examined a scenario in which the Primary Mission was modified to have 400,000 target stars observed with 4-minute sampling (maintaining the same data volume). The number of detected planets increased by about 15%. This suggests that 2-minute sampling is actually overkill for planet-detection purposes; to detect as many planets as possible it may make more sense to use longer time-sampling for a larger number of target stars, or to use shorter time sampling for the FFIs (and devote a larger fraction of the maximum data volume to the FFIs).

One possibility is to eliminate the short-cadence stars, and devote almost all the data volume to the FFIs. Exceptions could be made for a small number of especially interesting stars with short timescale variations. This would greatly reduce the effort needed to select and manage the list of target stars, and would probably simplify data processing and analysis by having only one predominant data product.

One benefit of finer time sampling to keep in mind is the greater accuracy with which transit times can be measured. This is because the ingress/egress durations are typically minutes. Based on work by Price & Rogers (2014), changing from 2-minute sampling to 30-minute sampling would lead to 2-3x increased uncertainty in the typical transit time. Of course, only a very small minority of stars have planets for which precise transit timing would be interesting.

SYNERGY WITH OTHER PROJECTS

JWST

Exoplanet observations with JWST will encompass transit, occultation, and phase curve measurements. It may be desirable for an Extended Mission to have a large overlap in sky coverage with the zones of greatest visibility for JWST (the ecliptic caps). JWST can observe targets within 5° of an ecliptic pole for the entire year. Targets within 10° can be observed for two-thirds of the year, and targets within 60° can be observed for one-third of the year.

The Simulations WG has studied this issue by asking: for each of the 6 nominal Extended Mission scenarios, how many new sub-Neptune planets are discovered within the JWST zones of greatest variability? And of those, how many of the simulated planets have properties that are favorable for detecting the atmospheric signals with JWST? The results are given in the tables below (taken from Bouma et al.).

Table 3: Newly detected sub-Neptune radius planets. $|\beta| > 85°$ can be observed all year by *JWST*; $|\beta| > 80°$ can be observed for $\geq$ two-thirds of the year, $|\beta| > 30°$ for $\geq$ one-third.

	$\|\beta\| > 85°$	$\|\beta\| > 80°$	$\|\beta\| > 30°$	All sky
primary	103	453	2088	2483
nhemi	38	170	1024	1284
npole	41	176	1419	1419
shemiAvoid	24	100	934	1327
elong	22	86	667	1169
eshort	12	52	857	1216
hemis14d	44	192	1130	1433

Table 4: $R_p > 4R_\oplus$ and $\mathrm{SNR}_{\mathrm{atm}} > \mathrm{SNR}_{\mathrm{GJ\ 1214b}}/2$.

	$\|\beta\| > 85°$	$\|\beta\| > 80°$	$\|\beta\| > 30°$	All sky
primary	1	4	71	104
nhemi	0	0	7	14
npole	0	0	8	8
shemiAvoid	0	0	8	24
elong	0	0	5	21
eshort	0	0	9	23
hemis14d	0	0	10	22

Table 5: $R_p > 4R_\oplus$ and $\mathrm{SNR}_{\mathrm{atm}} > \mathrm{SNR}_{\mathrm{GJ\ 1214b}}/5$.

	$\|\beta\| > 85°$	$\|\beta\| > 80°$	$\|\beta\| > 30°$	All sky
primary	21	83	1019	1361
nhemi	1	4	242	397
npole	1	4	278	278
shemiAvoid	1	3	261	523
elong	1	3	164	445
eshort	0	2	299	530
hemis14d	1	6	312	515

According to these results, there are relatively few detectable sub-Neptunes in the JWST continuous viewing zones that offer prospects for transmission spectroscopy that approach the well-studied system GJ 1214b. This is because the CVZs represent only 0.4% of the sky, and also because (according to the simulations) GJ 1214b is one of the most favorable systems that are ever likely to be found anywhere on the sky.

Another noteworthy result is that some of the Extended Mission scenarios are much better than others at detecting planets with ecliptic latitudes >80°. For example, ECL-SHORT detects four times fewer such planets than ALLSKY. Importantly, though, if we restrict our attention to planets with the very highest predicted SNR for atmospheric studies (e.g. at least 20% of the SNR of GJ 1214b) then there is practically no difference between the Extended Mission scenarios. This is because nearly all such planets can be detected in the Primary Mission. This suggests that the main synergy of TESS and JWST can be accomplished during the Primary Mission, and that the Extended Mission need not pay special attention to the ecliptic poles for the specific purpose of finding outstanding targets for JWST.

For interpreting these results it is worth emphasizing an assumption that was made by the Simulations WG. The assumption was that target stars would be selected by virtue of planet detectability according to a statistic (*Merit*) that is weighted by the square-root of the duration of observations. The relevant consequence is that for a given choice of sky-scanning strategy, zones that are observed for longer durations have fainter apparent magnitude limits. For example, in the simulated Primary Mission, the surface density of target stars near the ecliptic poles is roughly 3.5x higher than the surface density near the ecliptic. The actual prioritization scheme for TESS target stars may differ from this idealization.

An additional concern, probably minor, is that it might be impossible to perform precise JWST observations of very bright stars due to saturation or nonlinearity in the instruments. For example, for NIRSpec the saturation limit is anticipated to be J=6 for medium-resolution and J=11 for low-resolution observations. For standard NIRISS spectroscopy the saturation limit is J=8.1, and for subarray spectroscopy it is J=6.9 (Beichman 2014). Only a small number of the simulated TESS planet-hosting stars are brighter than these limits.

CHEOPS

Here we summarize the work of Berta-Thompson (2016), who examined how TESS and CHEOPS complement one other. CHEOPS provides more precise photometry for essentially all stars than TESS, and uses a narrow field of view to select individual targets. CHEOPS's visibility is best near the ecliptic, and non-existent near the ecliptic poles. TESS and CHEOPS could together measure TTVs, to both measure planet masses and also search for additional companions. As these systems will be accessible to radial velocities, they will be important keystones for cross-checking RV and TTV mass measurements. Obviously, Extended Missions that focus exclusively on the ecliptic poles (POLE) will minimize the overlap between TESS and CHEOPS visibility. Those that focus on the ecliptic will lead to the greatest mutual visibility.

MOST

Is the Canadian MOST spacecraft still operational, and potentially available for TESS follow-up?

GROUND-BASED TELESCOPES

One bonus of an Extended Mission that focuses on the ecliptic is that a larger number of ground-based observatories can participate in the follow-up. This has been made very clear through the recent experience of the K2 mission. On the other hand, it is somewhat more difficult to follow up on ecliptic targets because of the periodic interference from the Moon.

GROUND-BASED EXOPLANET SURVEYS

HAT, WASP, NGTS, MEarth, MASCARA, and other programs may still be running at the time of a TESS Extended Mission. Likewise there will be many ongoing Doppler planet-search programs. Are there any implications or special considerations for the design of an Extended Mission?

KEPLER

During the Primary Mission, most of the original Kepler field will be observed for 52 days. (A portion of the field may be observed for 78 days, and another portion for 26 days). Some reasons why TESS observations of Kepler objects might be interesting are:
a) detecting transits over a long baseline (e.g., to refine ephemerides);
b) measuring transit timing variations;
c) confirming few-transit KOI candidates (see, e.g., Wang et al. 2015, Uehara et al. 2016, Foreman-Mackey et al. 2016);
d) calibrating TESS against well-studied candidates,
e) continue observations of CBPs & multiple star systems, and
f) characterize stellar cycles over long timescales through star-spot measurements.

It is not obvious how useful TESS data will be for Kepler stars, because of the smaller collecting area and poorer angular resolution of TESS compared to Kepler. Sullivan (2013) explored TESS's anticipated performance on Kepler Objects of Interest (KOIs). He found 5-10% of the KOIs known at that time (October 2013) could be detected with SNR > 3 per transit. A few dozen of those planets are smaller than Neptune. Regarding the implications for an Extended Mission, the POLE scenario (applied to the northern hemisphere) would observe the Kepler field for 104 days, twice as long as HEMI, and yielding four times as much data as *ALLSKY*.

K2

The K2 mission uses the Kepler space telescope to observe a series of 10° fields on the ecliptic, for about 80 days per field. This zone surrounding the ecliptic nearly coincides with the zone that is not observed during the TESS Primary Mission. By the time of a TESS Extended Mission, K2 will probably have covered more than 60% of the area with ecliptic latitude <5°. Therefore, there will be many known transiting planets near the ecliptic. There will also be greater knowledge of eclipsing binaries and other variable stars near the ecliptic, which could be used for TESS target selection.

On the one hand, this suggests that TESS observations of the ecliptic would be valuable by extending the time baseline of K2 observations, and taking advantage of all the knowledge gained during the K2 mission. On the other hand, it could be argued that TESS observations near the ecliptic are redundant with K2 observations to some degree.

We note here that in the memorandum by Bouma et al. on selected scenarios for the Extended Mission, no attempt was made to for account any knowledge that might be gained from prior K2 observations. Many of the "new planets" that are reported in the simulations are likely to have been discoverable by the K2 mission.

CoRoT

It seems likely that the great majority of planet-hosting stars found by CoRoT are too faint to be profitably observed by TESS.

MOST

The MOST continuous viewing zone spans the declination range from –19° to +36°. Most of the MOST targets have been at roughly 40° in ecliptic latitude (retrieved MOST targets from http://www.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/en/search/?collection=MOST&noexec=true, Canadian Astronomy Data Center, August 21 2016).

GUEST INVESTIGATOR PROGRAM

Based on the experience of previous missions, the Guest Investigator (GI) program will play a very important role in maximizing the scientific achievements of the TESS mission. For this reason it is important for an Extended Mission to appeal to a very broad range of astronomers and enable a large variety of scientific projects. At this point, though, it is not clear what are the implications for the design of the Extended Mission. Careful attention should be paid to the GI proposals and outcomes during the Primary Mission, to gauge the demand for wide sky coverage versus long durations of observations for smaller regions of the sky. Other, unforeseen issues may arise from the GI process that may have implications for the Extended Mission. Close communication is strongly recommended between the GI office and the decision-makers for the Extended Mission. It may also make sense to solicit White Papers from the astronomical community for ideas regarding the Extended Mission, in the middle of the Primary Mission.