# Long Wavelength Array: Day in the Life Operation Model

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## 1. Introduction

The Long Wavelength Array (LWA) is designed as a user-oriented facility with capabilities across a wide area of Ionospheric and Space Science as well as Astrophysics. The design and development of the LWA is driven by the requirements which are outlined within the *Scientific Requirements Document* (LWA memo #117) and the *Probing the Ionosphere with the LWA by Rapid Cycling of Celestial Radio Emitters* memo (LWA memo # 128). Here we develop a sample observing program which extends over a 24 hour period of LWA use. The goal of this exercise is to provide an operational template which can be used to clarify the functionality that will drive the development of the hardware and software design, and data communications.

## 2. Science Requirements Summary

In this section we provide a brief summary of the key science drivers for the LWA as taken from LWA memo #117. Design of the Day in the Life operational model was driven by the desire to provide access to a broad range of low frequency astrophysical science.

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The key science drivers (KSDs) are:

1. Cosmic Evolution and the High Redshift Universe
   1.1 Dark Ages
   1.2 First Supermassive Black Holes
   1.3 Large Scale Structure - Dark Matter and Dark Energy
2. Acceleration of Relativistic Particles
   2.1 Up to $10^{15}$ eV in SNRs in Normal galaxies
   2.2 Up to $10^{19}$ eV in Radio Galaxies and Clusters of Galaxies
   2.3 Up to $10^{21}$ eV in Ultra High Energy Cosmic Rays
3. Plasma Astrophysics and Space Science
   3.1 Ionospheric Waves and Turbulence
   3.2 Solar, Planetary, and Space Weather Science
   3.3 Acceleration, Turbulence, and Propagation in the ISM of the Milky Way and Normal Galaxies
4. Exploration Science
   4.1 Emphasize Pioneering Capabilities for Survey and Discovery Space
   4.2 Transients and Extra-Solar Planets

Based on a review of the above science case, the Scientific Requirements Document outlined the specifications shown in Table 1 (taken directly from LWA memo # 117):

## Table 1. Key Science Specification Document Summary Table.[a]

| KSD[b] | $\nu_l$ - $\nu_u$ MHz | $\Delta\nu_{max}$ MHz | $\Delta\nu_{min}$[c] Hz | $\theta$ @ 80 MHz arcsec | $\Delta\tau$[d] ms | PBW $^\circ$ | LAS $^\circ$ | $\sigma$[e] mJy | $\Sigma$ mJy/bm | DR | Polz | ZaC $^\circ$ | Beams |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.1 | 7-88 | $\gtrsim 50$[e] | ··· | ··· | ··· | 1 | 1 | ··· | 1-10 mK (1 yr) | TBD | dual | ··· | 1[g] |
| 1.2 | 50-80 | ··· | ··· | $\lesssim 5$ | ··· | ··· | ··· | 9.2,5 | ··· | 902,740 | ··· | ···[h] | ··· |
| 1.3 | 20-80 | ··· | ··· | $\lesssim 5$ | ··· | $\gtrsim 1.5$ | $\gtrsim 1.5$ | 2.6,1 | 252,60 [$\theta$=1′] | 16700, 3700 | ··· | ··· | ··· |
| 2.1 | 20-80 | ··· | ··· | $\lesssim 5$ | ··· | $\gtrsim 5$ [@ 20 MHz] | $\gtrsim 1$ | 26,10 | 1 [$\theta$=20″] | 1670, 370 | ··· | $\lesssim 74$ | ··· |
| 2.2 | 20-80 | ··· | ··· | $\lesssim 2$ | ··· | ··· | ··· | 2.6,1 | 2 [$\theta$=6″] | 16700, 3700 | ··· | ··· | ··· |
| 2.3 | $\lesssim 60$ | $\gtrsim 33$ | ··· | ··· | $3\times10^{-5}$ | ··· | ··· | ··· | ··· | ··· | ··· | $\gtrsim 60$[i] | ··· |
| 3.1 | 9-80 | ··· | ··· | ··· | 1 | ··· | ··· | ··· | ··· | $10^4$ | dual | TBD | $\gtrsim 3$ |
| 3.2 | 20-80 | $\lesssim 60$ | 10 | 1 [@ 40 MHz] | $\lesssim 10$ | $\gtrsim 2$ | $\gtrsim 2$ | ··· | 500 mJy/arcmin$^2$ | $\gtrsim 4000$[j] | dual | $\lesssim 57$ | $\gtrsim 1$ |
| 3.3 | $\lesssim$ 10-88 | ··· | $\lesssim 100$ | 1.5 | ··· | ··· | 0.5 | ··· | 1 [$\theta$=10″ @ 30 MHz] | 20700 cont | dual | $\lesssim 74$ | ··· |
| 4.1 | 3-80 | Full RF | ··· | 2 | ··· | $\gtrsim 2$ | ··· | $\lesssim 1$ | ··· | $\gtrsim 3700$ | dual | ··· | $\gtrsim 1$ |
| 4.2 | 3-80 | ··· | TBD | ··· | $\lesssim 0.1$[k] | $\gtrsim 2$ | ··· | $\lesssim 1$ | ··· | $\gtrsim 3700$ | dual | $\lesssim 74$ | $\gtrsim 1$ |
| Required | 20-80 | 8[f] | $\lesssim 100$ | $\lesssim 2$ | 10[k] | 2 | 1 | 1[l] | | $10^4$, $10^3$ | dual | $\lesssim 60$ | 4[l] |
| Desired | 3-88 | $\gtrsim 50$ | 10 | $\lesssim 1$ | 1[k] | $\gtrsim 2$ | 2 | $\lesssim 1$[l] | | $10^5$, $10^4$ | dual | $\lesssim 74$ | $\gtrsim 7$[m] |

[a] Ranges of angular resolution, sensitivity, and dynamic range correspond to $\nu_l$ - $\nu_u$ unless otherwise specified. If only one number is given it applies to 80 MHz.

[b] Number refers to key science driver (KSD) category in Section 2.

[c] A minimum channel width of 1 kHz is necessary for RFI excision. Bandwidth smearing of $\lesssim$ 10% at the first null on 400 km baselines requires channel width less than 1.25 kHz.

[d] Time-averaging smearing of $\lesssim$ 10% at the first null on 400 km baseline for a 100 m station at 20 MHz requires temporal resolution be shorter than 0.9 s.

[e] Sensitivity is at 80 MHz except where two values are shown when the lower frequency cutoff is above 20 MHz. Numbers in latter case are for $\nu_l$, 80 MHz.

[f] Bandwidth requirement of $\gtrsim$ 50 MHz on baselines within 5-10 km for dark ages work.

[g] Shared beam day/night with Solar/Dark Ages.

[h] Studies of high redshift radio galaxies down to a zenith angle of 74° provides opportunity for full Keck/Gemini followup.

[i] Note that this is a dipole-based measurement.

[j] Requirement is a lower limt as it assumes 200 Jy quiescent disk for Sun at 80 MHz. CME are often associated with a powerful Solar burst which may be orders of magnitude brighter than the quiescent sun. DR requirement must be met on short enough timescale to track CME.

[k] Temporal resolution of 0.1 ms is needed to track the fastest pulsars. This exceeds the communication speed across full array and is only required for inner stations in phased-array mode. Require sampling at dipole level in a station of $3 \times 10^{-5}$ ms for UHECR work.

[l] Sensitivity in 1 hour, dual polarization, and 8 MHz bandwidth.

[l] The total required number of beams could be arrived at with various metrics for scientific output. The required number of 4 was arrived at assuming that there is a long terms dedicated Solar/DA beam plus three additional beams. Those three beams could be broken up to be a survey beam + a transient beam + a general observer beam, or the three could be combined for 3D ionospheric tomography work.

## 3. LWA

The LWA will consist of 52 stations which will fall into either 'core' stations which are located within a circular patch of roughly $10-15$ km in a centralized area or 'outlier' stations located well beyond this.

### 3.1. Day in the Life

Following the science case above as well as that described in LWA memos 117, 70, 49, and 10, and the ionospheric calibration scheme described in LWA memo 128, we have developed a template "Day in the Life" operation schedule for the LWA (Figure 1). The scientific and calibration observations using the LWA system are spread across several different 'beams' which have independent operation. For the purposes of this document a 'beam' is defined following the recommendation of LWA ECN001: "*Each beam can have N tunings, where N is 2 or greater <...>. Each tuning is characterized by a bandwidth, number of spectral channels, and temporal resolution. Multiple tunings can be used to provide a larger total bandwidth, up to N times the maximum bandwidth per tuning (currently specified as 8MHz). Each tuning is dual polarization and independently tunable.*" We further clarify that each 'beam' is capable of independent pointing direction. The number of independent beams associated with a particular station depends on the position of the station in the final array configuration. The system will ultimately consist of a 'core' area where there is a concentration of stations located in a region of $\sim$ 10 km diameter (LWA memo # 55) and 'outer' stations that provide longer baselines (up to 400 km). All stations (core and outer) will operate at least three beams (Beams $2-4$) while only the core stations will require the addition of the wide bandwidth beam (Beam 1) described below.

### 3.2. Beam Requirements

In this section we review the basic properties of each of the four LWA beams and provide a summary of instantaneous requirements for the beams. We base the requirements of the science cases on the numbers provided in LWA memo #117 and (for completeness) summarize the desired mode or shortfall of the DRX design outlined in LWA memo # 114.

#### *3.2.1. Beam 1: Dark Ages and Solar Science Beam*

This beam will be a dedicated beam shared between the Dark Ages science at night and Solar science during the day. The Dark Ages science will be confined to one or two individual pointings on the sky while the Solar science will be required to track the Sun across the sky (relative motion of 2.5 arcsec/minute to background sky).

### Solar:

The scientific goals of this beam are to track the solar bursts in frequency and time. Type III bursts drift very rapidly from high to low frequencies and are due to beams of fast electrons traveling away from the solar surface on open field lines. Type II bursts drift more slowly in frequency with time and often appear as two bands of emission. They are believed to be driven by shocks traveling at several times the local Alfvén speed. Type IV bursts appear as broadband continuum emission generally following a type II burst.

- Tracking Period: track Solar motion across the sky.
- Bandwidth: 60 MHz bandwidth to track solar activity. Following the definition above of a beam we therefore require 8 'tunings' to cover the full bandwidth.
  - $\Delta\nu_{max} = 60$ MHz ($7 \times 8$ MHz = 56 MHz is sufficient)
- Polarization: dual polarization
  - npol = 2
- Channel Width: sufficient channel resolution is needed to study fine structure details. According to Bastian et al. (1998) the structure width is a few percent of the emission frequency.
  - $\Delta\nu_{min} = 1$ kHz
- Temporal Resolution: temporal resolution of 10 ms is needed to track structure
  - $\Delta\tau = 10$ ms

Using the maximum required tuning bandwidth described above, the Solar science beam would require at minimum 7 of the 8 MHz tunings.

Based on the DRX high-level design memo v0.2 by Johnathan York (LWA memo #114) the Solar science beam would require at minimum 3 dual tuning DRX modules operating in

DRX mode 0 to be stacked contiguously in frequency. This (minimal hardware compromise) would provide 48 MHz of bandwidth, while the full bandwidth requirement above would need one additional DRX for a total of 64 MHz of bandwidth. This mode would only permit 3 kHz channels for RFI excision and insufficient spectral resolution for fine-scale structure.

### Dark Ages:

The scientific goal of this beam is to detect the 21-cm absorption signature when the spin temperature of the neutral hydrogen is decoupled from (and thus absorbs) the cosmic microwave background radiation. This occurs between a redshift of $20 \lesssim z \lesssim 200$ which corresponds to a frequency window of 71 MHz $\gtrsim \nu \gtrsim$ 7 MHz. Detections of this emission have the power to provide cosmological constraints that cannot be obtained by any other known method.

- Tracking Period: observations will be dedicated to one or two positions that will be continually observed
- Bandwidth: 50 MHz bandwidth is needed to obtain sufficient sensitivity to the signal over roughly one year of operation. *Based on discussions with Joe Lazio we note that the full 50 MHz may not be a critical requirement. More work is needed to review this.*
  - $\Delta\nu_{max}$ = 50 MHz ($7 \times 8$ MHz 'beams')
- Polarization: dual polarization
  - npol = 2
- Channel Width: 1 kHz channels are required for careful RFI excision. The ability to accurately remove RFI is critical to the successful detection of the signal. Increasing the channel width to 3 kHz in face of 10% of bandwidth impacted by RFI would increase the integration time by 25%. Channels of width 1.25 kHz or smaller are also required to avoid issues of bandwidth smearing.
  - $\Delta\nu_{min}$ = 1 kHz
- Temporal Resolution: sample data on timescale of roughly 1 second for calibration purposes. To avoid time averaging smearing the sampling time needs to be better than 0.9 s.
  - $\Delta\tau$= 0.9 s

A total of 7 tunings of 8 MHz each would provide a maximum bandwidth of 56 MHz which would meet the requirements for Dark Ages science.

Based on the DRX high-level design memo v0.2 by Johnathan York (LWA memo #114) the Dark Ages science beam would require at minimum 3 DRX modules operating in DRX mode 0 to be stacked contiguously in frequency. This would provide 48 MHz of bandwidth with 3 kHz channels. This channel width would not meet the RFI excision requirements nor the bandwidth smearing specification.

#### *3.2.2. Beam 2: Survey and Transients Beam*

This beam will be mainly dedicated to surveying the sky at a wide range of frequencies. When an internal or external transient trigger is activated for the LWA, the survey mode of this beam may be broken to follow up the transient event.

**Survey:**

During the survey mode of the instrument, the LWA will scan across the sky to build up an all-sky database. Priority will be given to lowest frequency survey work during times that the ionosphere is sufficiently quiescent as to permit viable observations at the lower end of the LWA frequency range. The instrument will cycle through observing frequencies based on comparison of real-time ionospheric conditions to pre-defined dynamic scheduling criteria. (We note that Beam 4 may provide the data necessary to evaluate the ionospheric conditions. Alternatively co-located GPS units have been suggested.) The depth of the sky survey will be built up over time to allow for dual use of the beam for obtaining both a deep multi-frequency survey as well as permitting transient detection capabilities by returning regularly to the same sky position. The survey mode may be used to undertake both continuum science as well as spectral line studies such blind searches for radio recombination lines from the cold interstellar medium.

- Tracking Period: each field will be tracked for $\sim$ 10 minutes before moving to the next field.
- Bandwidth: 8 MHz provides good sensitivity in reasonably short integrations for continuum survey work. For spectral line for (e.g. RRL ) we need a 10-20 % bandwidth.
  - $\Delta\nu_{max} = 8$ MHz
- Polarization: dual

- npol = 2

- Channel Width: 1 kHz channels are required for careful RFI excision. Channels of with 1.25 kHz or smaller are also required to avoid issues of bandwidth smearing. For spectral line survey work a channel width of 100 Hz may be required.
  - $\Delta\nu_{min} = 0.1$ kHz

- Temporal Resolution: sample data on timescale of roughly 1 second for calibration purposes. To avoid time averaging smearing the sampling time needs to be better than 0.9 s.
  - $\Delta\tau = 0.9$ s

The Survey science requirements will be met by a single tuning of 8 MHz.

Based on the DRX high-level design memo v0.2 by Johnathan York (LWA memo #114) the continuum Survey beam would require 1 DRX module operating in DRX mode 1. This would permit a total of 8 MHz of observing bandwidth and allow RFI excision in channels of 1.5 kHz width. The spectral line survey mode would require multiple (4-16) DRX modules operated in DRX mode 5. The proposed system design does not meet the science requirements in the case of RRLs if we limit the beam to one DRX. The DRX mode 5 needed for the channel width would permit a total bandwidth of only 500 kHz while Bill Erickson (private communication) had recommended 10-20% bandwidth to detect several simultaneous transitions.

## Transients:

The Transient science will initiate with either an internal trigger that is obtained from the near real-time image differencing of the all-sky map from the Survey beam or (more likely) based on an external trigger received from another instrument. The LWA will repoint to the best known position of the transient and begin a set of standard observations designed to help categorize the transient type. Once the type is known the transient beam will follow guidelines in an automated pipeline that define the observing procedure to follow.

- Tracking Period: a few minutes to a few hours

- Bandwidth: 8 MHz to provide good sensitivity on short timescales
  - $\Delta\nu_{max} = 8$ MHz

- Polarization: dual circular

  - npol = 2

- Channel Width: 1 kHz driven by RFI excision. Bandwidth smearing imposes a channel width of less than 1.25 kHz.

  - $\Delta\nu_{min} = 1$ kHz

- Temporal Resolution: 100 $\mu$s and longer for timing of the fastest pulsars

  - $\Delta\tau$= 100 $\mu$s and longer

The Transient science requirements will be met by a single tuning of 8 MHz.

Based on the DRX high-level design memo v0.2 by Johnathan York (LWA memo #114) the Transients beam would require 1 DRX module operating in DRX mode 0. The operation mode is forced by the timing requirement and may be relaxed for non-pulsar transient work. This operation mode will force RFI excision in channels of 3 kHz width which is not desirable, and will also fail to meet the bandwidth specification.

#### *3.2.3. Beam 3: General Observer Beam*

This beam will provide the user flexibility of the instrument. It will be dedicated to observing programs proposed by the user community that have been approved through the peer review process. Below we briefly outline science cases based on LWA memo # 117 where a single DRX in the configuration suggested by LWA memo #114 cannot meet the science requirements. This beam will cover science over the full range of ionospheric and astrophysical interests and thus a wide range of capabilities are necessary to satisfy the requirements. In particular we point out that the RFI excision, bandwidth smearing,and temporal smearing requirements stated above are equally applicable to this beam.

**KSD 2.3:** UHECR studies require an instantaneous bandwidth of > 33 MHz at individual dipoles. Note however that this is a special requirement as it needs hardware capable of recording a signal from each dipole at the station level.

**KSD 3.2:** Planetary radar studies require at least 10 Hz spectral resolution as the total Doppler spreads of Mercury and Venus at 75 MHz are a few Hz.

**KSD 3.3:** RRL studies need 10-20% bandwidth (2-8 MHz) and spectral resolution of 100 Hz.

### *3.2.4. Beam 4: Calibration Beam*

This beam is dedicated to the calibration of the LWA and may also be employed as part of a 3D Ionospheric Tomography project beam which would simultaneously make use of Beams 2 and 3. Details of the ionospheric calibration scheme are presented in LWA memo # 128. The requirements below are based on that memo. The calibration beam is critical for providing a first pass of self-calibration based ionospheric corrections to apply to all observations underway with the LWA. The beam will be used to re-construct a model of the ionosphere over the full sky visible to the LWA during each calibration cycle (i.e. in less than 10 seconds including overhead). In addition to the astronomical calibration aspect of this beam, it is also anticipated that the output ionospheric temporal model will provide valuable input to the ionospheric scientific community.

We also anticipate that we will require a short amount of time on a near daily basis which should be dedicated to system maintenance. Since all beams sample the same data stream there is likely no need to regularly tap all beams for maintenance purposes. We suggest that short periods of time could be allocated within Beam 4 for the regular maintenance. On a more extended timescale of one to several weeks there could be short maintenance periods set to tap the other beams to ensure global data quality.

- Tracking Period: integrate on sources for timescales of 10 to 200 ms before moving to next source.
- Bandwidth: 8 MHz bandwidth to allows sub-band calibration to recover delta TEC. Additional bandwidth may provide expanded ionospheric analysis capabilities.
  - $\Delta\nu_{max}$ = 8 MHz
- Polarization: dual polarization
  - npol = 2
- Channel Width: channels must be sufficiently small to allow accurate RFI excision.
  - $\Delta\nu_{min}$ = 1 kHz
- Temporal Resolution: one integration per source observation should be sufficient
  - $\Delta\tau$= 10 ms
- Re-pointing timescale: the overhead time needed to move to a new target and have stable observations underway should not exceed $10-20\%$ of the total calibration cycle

– $\Delta\tau_{switch}= 5 - 10$ ms

The Calibration Beam requirements will be met by a single tuning of 8 MHz.

Based on the DRX high-level design memo v0.2 by Johnathan York (LWA memo #114) the calibration beam would be satisfied by DRX mode 1. Moving to DRX mode 0 would allow for a total of 16 MHz of usable bandwidth for expanded ionospheric analysis capabilities with the RFI excision capabilities reduced to 3 kHz channels. This would likely be sufficient for self-calibration of the brightest sources and the bandwidth gained by the trade-off of going to DRX mode 0 may permit more advanced ionospheric analysis through the expanded sensitivity and/or wider frequency baselines.

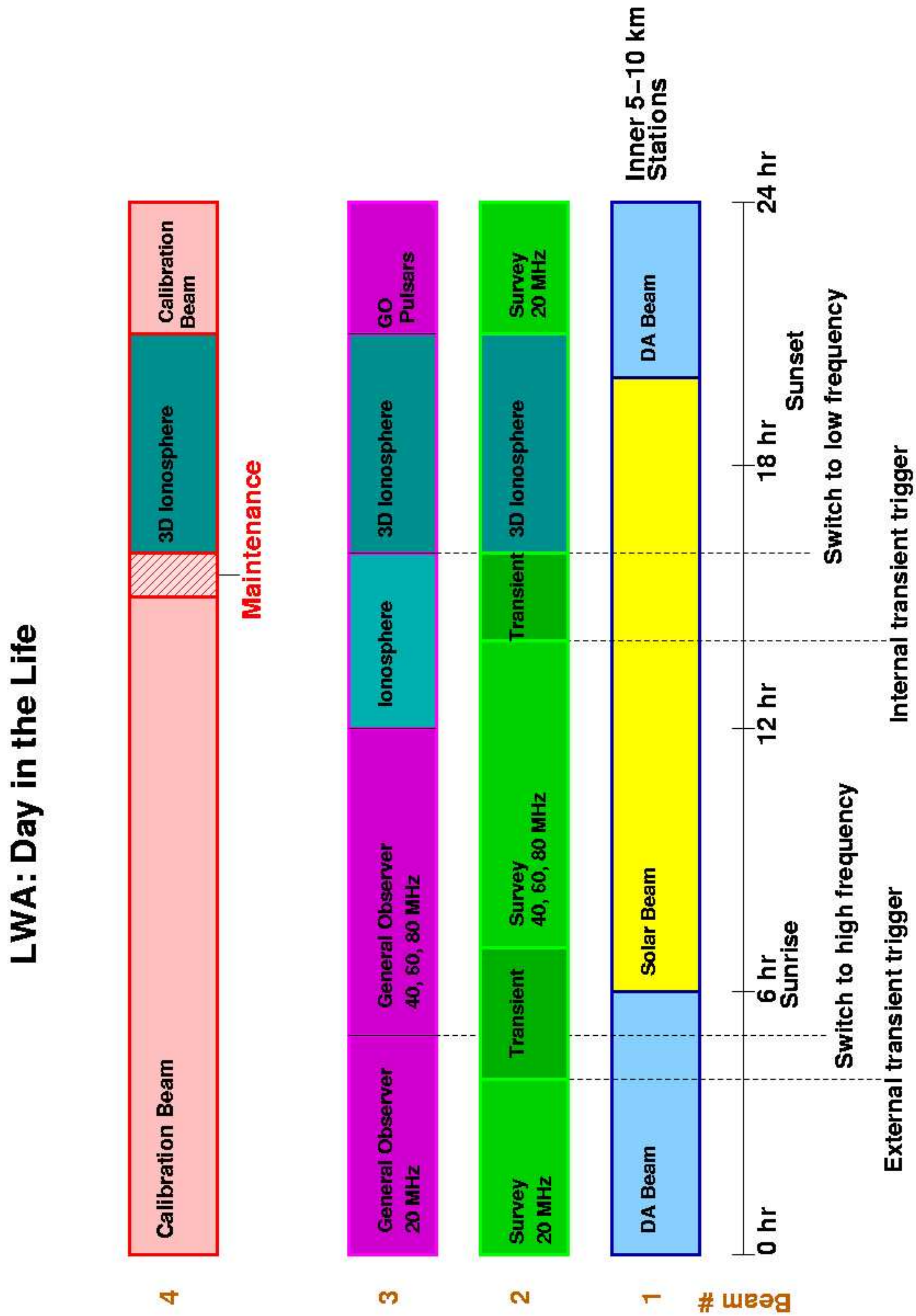


*Figure 1:* Sample 24 hour operational template for the Long Wavelength Array showing typical scheduling requirements.

## 4. Version History

The history for development of this document is:

- Version 0.1: Draft to Dan Wood
- Version 0.2: Revised draft to LWA scientific users
- Version 0.5: Revisions from Cohen and Kassim
- Version 1.0: Additional revisions. Submitted Memo

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