This talk is an overview of the process to assimilate MSE’s science capabilities into tangible design requirements scientists and engineers can use to build a physical observatory.

Specifically, this talk describes:

• Organization of the Science Requirements Document
• Division of science requirements into Level 1 Documents – OAD, OCD & ORD
  • Requirement flow-down
• Current predictions of MSE’s system performance
  • Evaluation based on the conceptual design
• Proposed actions in the Preliminary Design Phase to refine the science requirements
Key science drivers in the Detailed Science Case are captured in the Science Requirements Document. The SRD represents the highest level of science products that MSE must deliver.

Using standard systems engineering practices, we convert the SRD requirements into engineering requirements in design, system performance budgets and operation processes in the Level 1 Documents:

- Observatory Architecture Document
- Operations Concept Document
- Observatory Requirements Document
The Science Requirements Document is organized in five groups:

1. Spectral resolution
2. Focal plane input
3. Sensitivity
   - 3a. Spectral coverage
   - 3b. SNR
4. Calibration
5. Lifetime operations
The SRD requirements are divided into engineering requirement categories:

- Design
- System performance budgets
- Calibration procedures
- Operation procedures

in the OAD and OCD.

The SRD requirements are “fulfilled” by the Level 1 Documents.
SRD Compliance Summary

Color code illustrates the compliance of the SRD requirements as fulfilled by the Level 1 Documents:

1. Spectral resolution
2. Focal plane input
3. Sensitivity
   - 3a. Spectral coverage
   - 3b. Sensitivity
4. Calibration
5. Lifetime operations

Compliant assessment (Y/N/Partial/TBD)

- **Y** means fully meet requirement
- **TBC** means by design or analysis the requirement is already met but we plan to do more work in the Preliminary Design Phase before declaring compliance.
- **Partial** means formal declaration needed from the Project Office to claim compliance.
- **Partial** means a portion of a multiple-part requirement is met.
"Traffic-light" summary of requirement groups compliance:

1. Spectral resolution
2. Focal plane input
3a. Spectral coverage
3b. Sensitivity
4. Calibration
5. Lifetime operations

Prioritize our discussion on the red to yellow color requirement groups only:

- 3b. Sensitivity
- 1. Spectral resolution
- 4. Calibration
- 2. Focal plane input

### Requirements relating to Spectral Resolution:

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Compliance</th>
</tr>
</thead>
<tbody>
<tr>
<td>REQ-SRD-011</td>
<td>Partial</td>
</tr>
<tr>
<td>REQ-SRD-012</td>
<td>Partial</td>
</tr>
<tr>
<td>REQ-SRD-013</td>
<td>Y</td>
</tr>
</tbody>
</table>

### Requirements relating to the Focal Plane Input:

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Compliance</th>
</tr>
</thead>
<tbody>
<tr>
<td>REQ-SRD-021</td>
<td>Y</td>
</tr>
<tr>
<td>REQ-SRD-022</td>
<td>Partial</td>
</tr>
<tr>
<td>REQ-SRD-023</td>
<td>Partial</td>
</tr>
<tr>
<td>REQ-SRD-024</td>
<td>Y</td>
</tr>
<tr>
<td>REQ-SRD-025</td>
<td>Y</td>
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### Requirements relating to Sensitivity:

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Compliance</th>
</tr>
</thead>
<tbody>
<tr>
<td>REQ-SRD-031</td>
<td>Y</td>
</tr>
<tr>
<td>REQ-SRD-032</td>
<td>Y</td>
</tr>
<tr>
<td>REQ-SRD-033</td>
<td>Y</td>
</tr>
<tr>
<td>REQ-SRD-034</td>
<td>Partial</td>
</tr>
<tr>
<td>REQ-SRD-035</td>
<td>Y</td>
</tr>
<tr>
<td>REQ-SRD-036</td>
<td>Y</td>
</tr>
</tbody>
</table>

### Requirements relating to Calibration:

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Compliance</th>
</tr>
</thead>
<tbody>
<tr>
<td>REQ-SRD-041</td>
<td>TBC</td>
</tr>
<tr>
<td>REQ-SRD-042</td>
<td>TBC</td>
</tr>
<tr>
<td>REQ-SRD-043</td>
<td>TBC</td>
</tr>
<tr>
<td>REQ-SRD-044</td>
<td>Y</td>
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<tr>
<td>REQ-SRD-045</td>
<td>Y</td>
</tr>
<tr>
<td>REQ-SRD-046</td>
<td>Y</td>
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### Requirements relating to Lifetime Operations:

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Compliance</th>
</tr>
</thead>
<tbody>
<tr>
<td>REQ-SRD-051</td>
<td>Y</td>
</tr>
<tr>
<td>REQ-SRD-052</td>
<td>Y</td>
</tr>
<tr>
<td>REQ-SRD-053</td>
<td>Y</td>
</tr>
</tbody>
</table>
The sensitivity requirements are defined according to resolution modes for a one hour exposure at a given target flux, sky brightness, airmass and image quality.

- No explicit requirements for <370 nm
- Airmass of 1.2
  - 30° zenith
- Median IQ expected at prime focus

<table>
<thead>
<tr>
<th>Resolution</th>
<th>SNR/Resolution Element</th>
<th>Science Target Flux Density, $F_{obj}$</th>
<th>Sky Brightness, V-Band, $F_{sky}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LR</td>
<td>≥1</td>
<td>≥2</td>
<td>9.1xE-30 (m=24) 20.7</td>
</tr>
<tr>
<td>MR</td>
<td>≥1</td>
<td>≥2</td>
<td>1.4xE-29 (m=23.5) 20.7</td>
</tr>
<tr>
<td>HR</td>
<td>≥5</td>
<td>≥10</td>
<td>3.6xE-28 (m=20) 19.5</td>
</tr>
</tbody>
</table>

[REQ-SRD-034] In the low resolution mode, an extracted spectrum from MSE taken in the observing conditions described below shall have a signal to noise ratio per resolution element at a given wavelength that is greater than or equal to two for a 1 hour observation of a point source with a flux density of $9.1 \times 10^{-30}$ ergs/sec/cm$^2$/Hz at that wavelength, for all wavelengths longer than 400nm. Between 370 – 400nm, the SNR shall not be less than one at any wavelength. The observing conditions in which this requirement shall be met correspond to a sky brightness of $20.7\text{mags/sq.arcsec}$ in the V-band at an airmass of 1.2, and a delivered image quality at that airmass of 0.6 arcseconds full width at half maximum in the r band.

[REQ-SRD-035] In the moderate resolution mode, an extracted spectrum from MSE taken in the observing conditions described below shall have a signal to noise ratio per resolution element at a given wavelength that is greater than or equal to two for a 1 hour observation of a point source with a flux density of $1.4 \times 10^{-29}$ ergs/sec/cm$^2$/Hz at that wavelength, for all wavelengths longer than 400nm. Between 370 – 400nm, the SNR shall not be less than one at any wavelength in the relevant window. The observing conditions in which this requirement shall be met correspond to a sky brightness of $20.7\text{mags/sq.arcsec}$ in the V-band at an airmass of 1.2, and a delivered image quality at that airmass of 0.6 arcseconds full width at half maximum in the r band.

[REQ-SRD-036] In the high resolution mode in any wavelength window observed over the lifetime of MSE, an extracted spectrum from MSE taken in the observing conditions described below shall have a signal to noise ratio per resolution element at a given wavelength that is greater than or equal to ten for a 1 hour observation of a point source with a flux density of $3.6 \times 10^{-28}$ ergs/sec/cm$^2$/Hz at that wavelength, for all wavelengths in the relevant window longer than 400nm. Between 370 – 400nm, the SNR shall not be less than five at any wavelength in the relevant window. The observing conditions in which this requirement shall be met correspond to a sky brightness of $19.5\text{mags/sq.arcsec}$ in the V-band at an airmass of 1.2, and a delivered image quality at that airmass of 0.6 arcseconds full width at half maximum in the g band.
Sensitivity plots show the SNR achieved by the conceptual design for three resolution modes:

- Dashed cyan curves show SRD requirements.
- Within each resolution mode, the sensitivity plot is segmented according to the spectral coverage stated in the SRD.
Low resolution sensitivity requirement met except in the NIR

- Compliant in visible-band (≤ 950 nm)
- Not compliant in J-band
- Not compliant in H-band
Low resolution sensitivity requirement met except in the NIR

- Compliant in visible-band (≤ 950nm)
- Not compliant in J-band
- Not compliant in H-band

Proposed actions:

- H-band consideration
  - Even if there was no sources of noise in addition to sky and target noise, it is physically impossible to meet current science requirement.
  - Consult with scientists to revise SNR requirement, e.g. increase science target intrinsic flux density by 0.5 magnitude, from m=24 to m=23.5.
    » A formal change control process requires Management Group approval and consultation with Science Advisory Group
- J-band consideration
  - Confirm sky model used is appropriate for Maunakea
Moderate resolution sensitivity requirement fully met
High resolution sensitivity requirement is met, except where the spectral resolution was changed from R20K to R40K during the Conceptual Design Phase

- Compliant for wavelength $\geq 500$ nm where spectral resolution is R20K
- Not compliant where spectral resolution is R40K
High resolution sensitivity requirement met, except where spectral resolution was changed from R20K to R40K during the Conceptual Design Phase

- Compliant for wavelength range ≥ 500 nm where spectral resolution is R20K
- Not compliant where spectral resolution is R40K

Proposed actions:
- Consult with scientists to determine the highest resolution required within the intent of science motivation.
  - SRN requirement at R40K is challenging to achieve
- Conducting feasibility study of moving the HR spectrographs to the telescope instrument platforms in order to shorten the fiber bundles and increase blue throughput
Spectral Resolution – LR Mode

[REQ-SRD-011] MSE shall provide a mode with an average spectral resolution of $2500 \leq R \leq 3000$ at optical wavelengths ($\lambda < 950\text{nm}$, TBC), with a minimum resolution of $R > 2000$ at optical wavelengths, and a minimum spectral resolution of at least $R = 3000$ (Goal: $R = 5000$) at near infrared wavelengths ($\lambda > 950\text{nm}$, TBC).

<table>
<thead>
<tr>
<th>Wavelength Range</th>
<th>LR Mode</th>
<th>Required Average Resolution</th>
<th>Achieved Average Resolution</th>
<th>Required Minimum Resolution</th>
<th>Achieved Minimum Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda &lt; 950\text{nm}$</td>
<td>$\lambda &gt; 950\text{nm}$</td>
<td>$2500 \leq R \leq 3000$</td>
<td>$3396$</td>
<td>$R &gt; 2000$</td>
<td>$1983$</td>
</tr>
</tbody>
</table>

- Achieved low spectral resolution in LMR spectrograph
  - For $\lambda < 950\text{nm}$, average resolution $R = 3396$ $\lambda_{\text{max}} \sim 13\%$
  - For $\lambda < 950\text{nm}$, minimum resolution $R = 1983$ $\lambda_{\text{min}} \sim 1\%$
Spectral Resolution – LR Mode

1. Spectral resolution

[REQ-SRD-011] MSE shall provide a mode with an average spectral resolution of $2500 \leq R \leq 3000$ at optical wavelengths ($\lambda < 950\text{nm}$, TBC), with a minimum resolution of $R > 2000$ at optical wavelengths, and a minimum spectral resolution of at least $R = 3000$ (Goal: $R = 5000$) at near infrared wavelengths ($\lambda > 950\text{nm}$, TBC).

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<tbody>
<tr>
<td>$\lambda &lt; 950\text{nm}$</td>
<td>$\lambda &gt; 950\text{nm}$</td>
<td>$2500 \leq R \leq 3000$</td>
<td>$3396$</td>
<td>$R &gt; 2000$</td>
<td>$1983$</td>
</tr>
<tr>
<td>$\lambda &gt; 950\text{nm}$</td>
<td>$\lambda &gt; 950\text{nm}$</td>
<td>$-$</td>
<td>$-$</td>
<td>$R &gt; 3000$</td>
<td>$3190$</td>
</tr>
</tbody>
</table>

- Achieved low spectral resolution in LMR spectrograph
  - For $\lambda < 950\text{nm}$, average resolution $R = 3396 > \lambda_{\text{max}} \sim 13\%$
  - For $\lambda < 950\text{nm}$, minimum resolution $R = 1983 < \lambda_{\text{min}} \sim 1\%$

Proposed actions:
- Consult with scientists to determine if the achieved average and minimum resolutions, at LR mode, are within the intent of science motivation.
Spectral Resolution – MR Mode

1. Spectral resolution

[REQ-SRD-012] MSE shall provide a mode with an average spectral resolution of $5000 \leq R \leq 7000$ in each wavelength window, with a minimum spectral resolution within each window of $R > 4500$.

- Achieved moderate spectral resolution in LMR spectrograph
  - Average resolution $R_{Blue} = 3822 < \lambda_{min} \sim 24\%$
  - Minimum resolution $R_{Blue} = 3788 < \lambda_{min} \sim 16\%$
Spectral Resolution – MR Mode

1. Spectral resolution

[REQ-SRD-012] MSE shall provide a mode with an average spectral resolution of $5000 \leq R \leq 7000$ in each wavelength window, with a minimum spectral resolution within each window of $R > 4500$.

<table>
<thead>
<tr>
<th>MR Mode</th>
<th>Wavelength Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Required Average Resolution</td>
<td>$5000 \leq R \leq 7000$</td>
</tr>
<tr>
<td>Achieved Average Resolution</td>
<td>$R_{Blue} = 3822$</td>
</tr>
<tr>
<td>Achieved Average Resolution</td>
<td>$R_{Green} &gt; 5000$</td>
</tr>
<tr>
<td>Achieved Average Resolution</td>
<td>$R_{Red} &gt; 5000$</td>
</tr>
<tr>
<td>Required Minimum Resolution</td>
<td>$R &gt; 4500$</td>
</tr>
<tr>
<td>Achieved Minimum Resolution</td>
<td>$R_{Blue} = 3788$</td>
</tr>
<tr>
<td>Achieved Minimum Resolution</td>
<td>$R_{Green} &gt; 4500$</td>
</tr>
<tr>
<td>Achieved Minimum Resolution</td>
<td>$R_{Red} &gt; 4500$</td>
</tr>
</tbody>
</table>

- Achieved moderate spectral resolution in LMR spectrograph
  - Average resolution $R_{Blue} = 3822 < \lambda_{min} \sim 24\%$
  - Minimum resolution $R_{Blue} = 3788 < \lambda_{min} \sim 16\%$

Proposed actions:
- Consult with scientists to determine if the achieved average and minimum resolutions from the blue spectral arm of the MR mode are within the intent of science motivation.
[REQ-SRD-013] MSE shall provide a mode with an average spectral resolution of $38000 \leq R \leq 42000$ in wavelength windows at $\lambda \leq 500\text{nm}$, with a minimum spectral resolution within these windows of $R > 35000$ (ii) an average spectral resolution of $18000 \leq R \leq 22000$ in any wavelength windows at $\lambda \geq 500\text{nm}$, with a minimum spectral resolution within these windows of $R > 15000$ (TBC).

<table>
<thead>
<tr>
<th>Wavelength Range</th>
<th>HR Mode</th>
<th>$\lambda &lt; 500\text{nm}$</th>
<th>$\lambda &gt; 500\text{nm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Required Average Resolution</td>
<td>38000\leq R \leq 42000</td>
<td>18000\leq R \leq 22000</td>
<td></td>
</tr>
<tr>
<td>Achieved Average Resolution</td>
<td>$R_{\text{Blue}} = 40000$</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Achieved Average Resolution</td>
<td>$R_{\text{Green}} = 40000$</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Achieved Average Resolution</td>
<td>-</td>
<td>$R_{\text{Red}} = 20000$</td>
<td></td>
</tr>
<tr>
<td>Required Minimum Resolution</td>
<td>$R &gt; 35000$</td>
<td>$R &gt; 15000$</td>
<td></td>
</tr>
<tr>
<td>Achieved Minimum Resolution</td>
<td>$R_{\text{Blue}} &gt; 35000$</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Achieved Minimum Resolution</td>
<td>$R_{\text{Green}} &gt; 35000$</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Achieved Minimum Resolution</td>
<td>-</td>
<td>$R_{\text{Red}} &gt; 15000$</td>
<td></td>
</tr>
</tbody>
</table>

- HR spectrograph spectral resolution is fully compliant.
• Recognizing calibration is of critical importance, a dedicated talk to discuss calibration issues

• Velocity accuracy for LR and MR
  • The required velocity accuracy is the intrinsic velocity precision for each spectral resolution. We expect requirements can be achieved with low risk after further analysis.

• Velocity accuracy for HR
  • This velocity accuracy is several factors better than the intrinsic velocity precision for this resolution; however it is attainable by comparison with what other similar facilities have already achieved.

• Sky subtraction of emission lines
  • Need to complete simulations of sky subtraction in regions of bright sky lines before affirming compliance using the latest sky subtraction techniques.
<table>
<thead>
<tr>
<th>Multiplexing Requirements</th>
<th>SRD</th>
<th>Conceptual Design</th>
<th>After 2%* failure rate</th>
<th>% Diff from SRD req’n</th>
</tr>
</thead>
<tbody>
<tr>
<td>LR mode</td>
<td>&gt;3200</td>
<td>3249</td>
<td>3184</td>
<td>-0.5%</td>
</tr>
<tr>
<td>MR mode</td>
<td>&gt;3200</td>
<td>3249</td>
<td>3184</td>
<td>-0.5%</td>
</tr>
<tr>
<td>HR mode</td>
<td>&gt;1000</td>
<td>1083</td>
<td>1061</td>
<td>+6.1%</td>
</tr>
</tbody>
</table>

*2% failure rate is based on historical data from the Subaru FMOS echidna positioners.
Focal Plane Input

Proposed actions:
• Project Office to declares the multiplexing requirements are fully met.

*2% failure rate is based on historical data from the Subaru FMOS echidna positioners.
Summary

- We have a conceptual design that meets the MSE science capabilities in the optical and NIR bands for target magnitude=24 for over 3200 targets
- Except the stated non-compliances
- Working with the Science Team, we believe we will meet all SRD requirements.
We Need Your Inputs (1)

For LMR science considerations:
- What are the minimum sensitivities required for J-band and H-band in low resolution?
- What is the appropriate H-band limiting mag. for the low resolution science required?
  - For example, is m=23.5 acceptable?
- What is the anticipated target density in H-band?
  - 2200/sq. degrees is assumed in the SRD, same as the optical band
  - If the target density is lower, does having standalone H-band spectrograph make sense?
- Can we do away with H-band LR mode all together?
- What are the science motivations of the LR and MR resolutions, average and minimum?
  - Can we do away with MR mode all together?
We Need Your Inputs (2)

- For HR science considerations:
  - What is the minimum SNR and resolution for $\lambda < 500$ nm?
  - For example, is SNR=5 acceptable, instead of 10?
  - For example, is R35K acceptable, instead of R40k, in order to increase SNR?
  - What are the science appropriate central wavelengths for the blue, green and red spectral arms given the $\lambda/30$ and $\lambda/15$ working windows?
• Compliance reported at the System Design Review

• Compliance based the planned PO work outlines in this talk

• Compliance with your inputs and feedback moving forward
The Maunakea Spectroscopic Explorer (MSE) conceptual design phase was conducted by the MSE Project Office, which is hosted by the Canada-France-Hawaii Telescope (CFHT). MSE partner organizations in Canada, France, Hawaii, Australia, China, India, and Spain all contributed to the conceptual design. The authors and the MSE collaboration recognize the cultural importance of the summit of Maunakea to a broad cross section of the Native Hawaiian community."
5. Lifetime operations

- Accessible sky requirement is confirmed by the subsystem conceptual designs.
- Observing efficiency is achieved by its own budget.

\[
\text{Obs. Eff} = \frac{\text{nighttime spent collecting photons}}{\text{all nighttime} - \text{nighttime lost to weather}}
\]
- The Observing Efficiency Budget specifies the observing sequence, science and operation overheads, and allowable failure rates of subsystems.
5. **Lifetime operations**

- Accessible sky requirement is confirmed by the subsystem conceptual designs.
- Observing efficiency is specified by its own budget.

\[
\text{Obs. Eff} = \frac{\text{nighttime spent collecting photons}}{\text{all nighttime} - \text{nighttime lost to weather}}
\]

- The Observing Efficiency Budget specifies the observing sequence, science and operation overheads, and allowing failure rates of subsystems.

- **Observatory lifetime requirement** flow-down to the components’ design life* requirements in the ORD:
  - Structural components – indefinite
  - Telescope optical components – 35 years
  - Instrumentation – 20 years
  - Electrical and electronic components – 20 years

*with preventative maintenance