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Figures of Merit: A Useful Standard for Lunar Simulants

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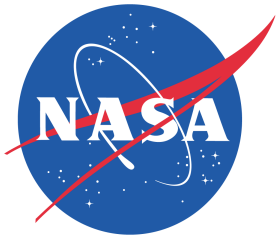

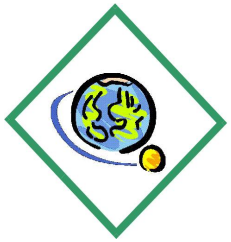

ISO 10788(E)

Space Systems – Lunar Simulants

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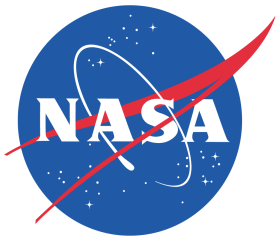
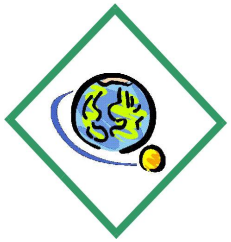
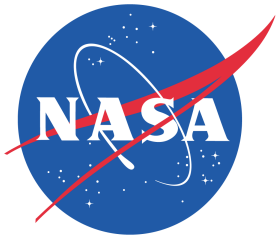
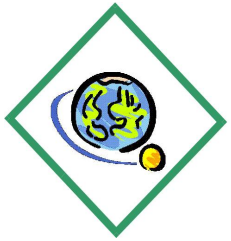




Quantitative Properties of Lunar Simulants

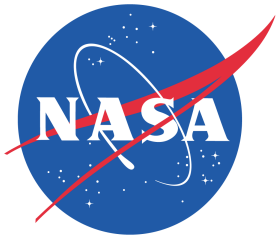
- Lunar simulants may be measured as lunar samples were measured and published (for example, reference Lunar Sourcebook) However, the quality of lunar simulants measured in this way cannot be readily compared to lunar source material nor communicated across development and operational communities. Comparison of these measures for simulants is not recommended.

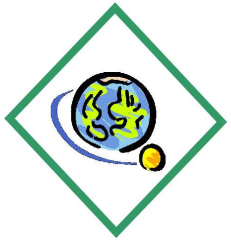




Need for a Qualitative Standard for lunar simulants

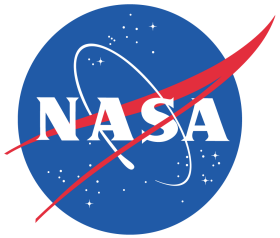
- The challenge in developing a useful standard is that the lunar surface has many selenological characteristics with high variability. Additionally, there are relatively few actual samples to work with from just a handful of locations.
- In an effort to communicate among the diverse technical communities performing research on, or research using regolith samples and simulants, a set of Figures of Merit (FoM) have been devised. The objective is to allow consistent and concise comparative communication between researchers from multiple organizations and nations engaged in lunar exploration.
- ISO 10788 captures the existing development effort

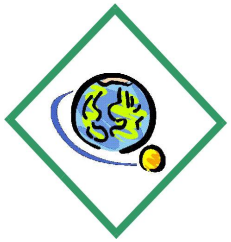




Four Figures of Merit

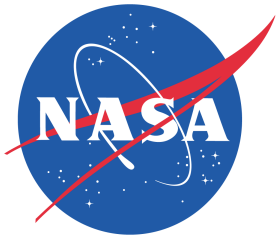
- Composition FoM
- Size Distribution FoM
- Shape Distribution FoM
- Density FoM

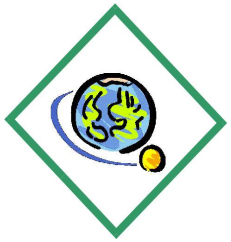




Simulant Quality
Impurities and Contamination

- Simulants may not be completely defined by these Figures of Merit for reasons of mineralogical impurity and contamination of the simulant by organic/inorganic materials.
  - Impurity of the sample/simulant measured shall be stated in percent of the sample mass.
  - Contamination of the sample/simulant shall be stated in percentage of the sample volume. Characterization of the sample contamination and the nature of that contamination shall be stated if an analysis is performed.





Composition FoM

- The Figures of Merit is defined as the scaled L1 norm of the difference of two composition vectors subtracted from unity.

- Scaling (normalization) forces the norm of the difference of two composition vectors to lie between 0 and 1, and subtraction from unity results in a figure of merit of 1 for a perfect match to 0 for no match at all (as opposed to the other way around).

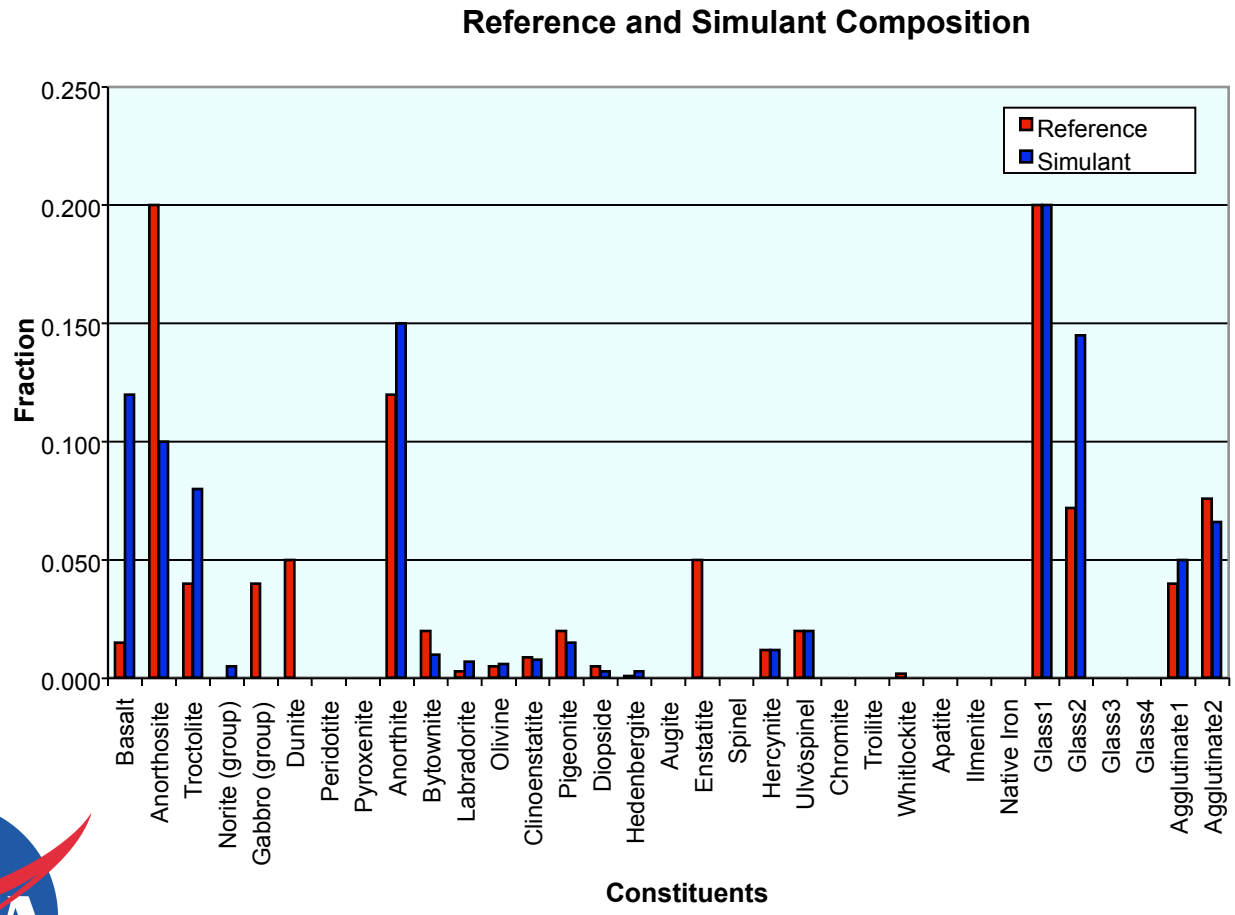
$$FoM = 1 - \frac{\left\| w_{adjusted} \left(c_{adjusted\ reference} - c_{adjusted\ simulant} \right) \right\|_1}{\left\| \left[\max_1 \left(w_{adjusted} \right) \quad \max_2 \left(w_{adjusted} \right) \right] \right\|_1}$$

$$\max_i (w)\ is\ i^{th}\ largest\ element\ of\ w$$

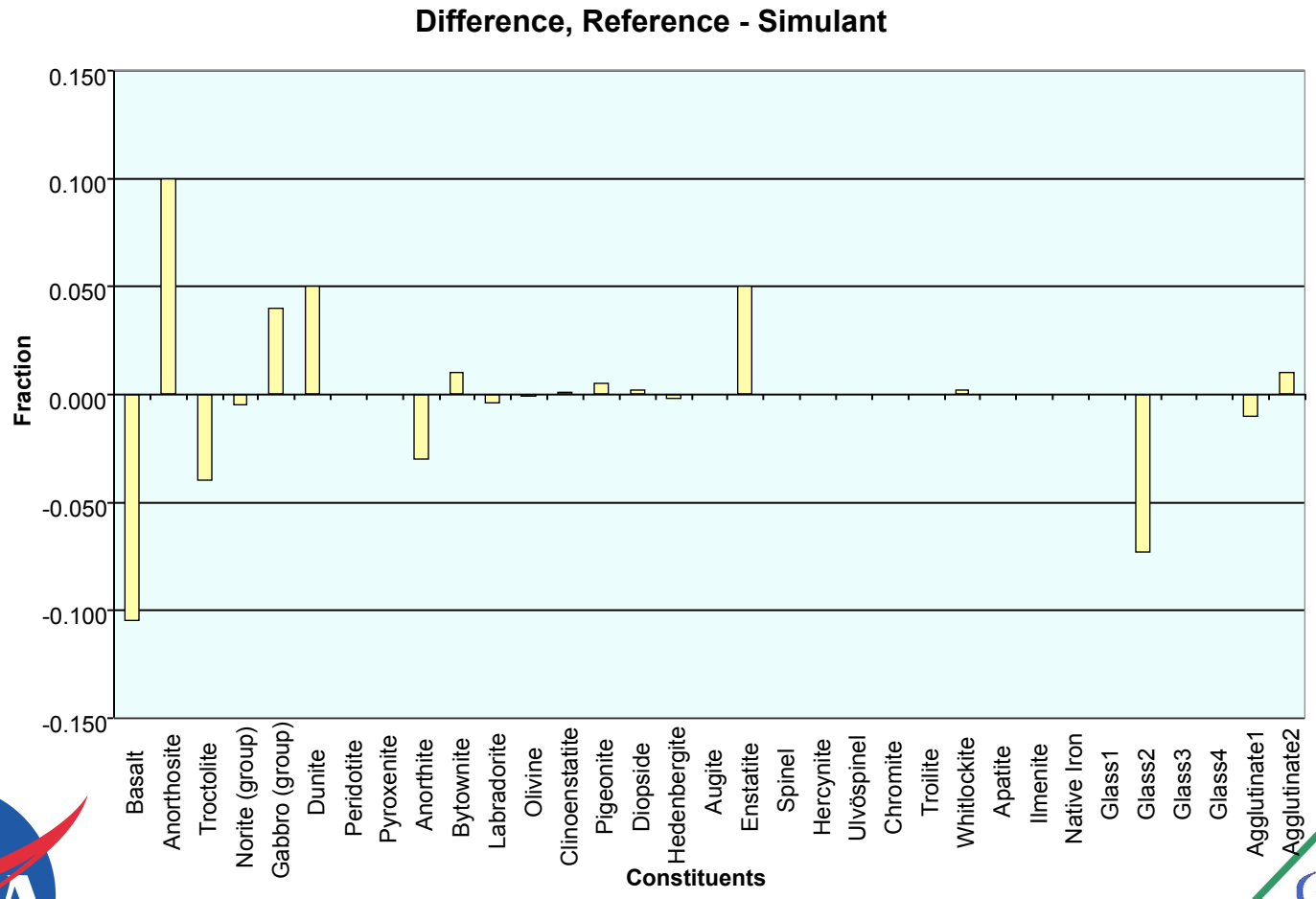
– The L1 norm of a vector is defined as the sum of the absolute values of the elements of the vector.

Composition FoM

Composition vectors displayed as a bar chart (example)



Composition FoM
Difference of composition vectors (example)



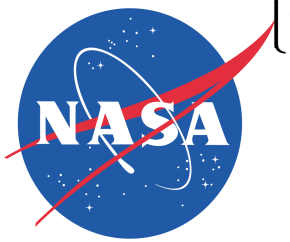
Size Distribution FoM

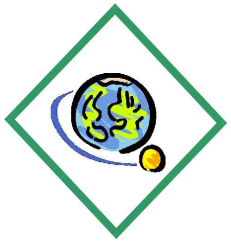
- The FoM for a given reference and simulant relative frequency distributions is defined as 1 minus the square root of the integral of the weighted difference of the RFDs squared divided by the sum of the weighted integrals of the squares of the individual RFDs.

$$FoM_{before\ constraints} = 1 - \frac{\sqrt{\int w\left(RFD_{reference} - RDF_{simulant}\right)^2}}{\sqrt{\int w\,RFD^2_{reference} + \int w\,RFD^2_{simulant}}}$$

- The FoM is further subject to certain maximum error constraints:

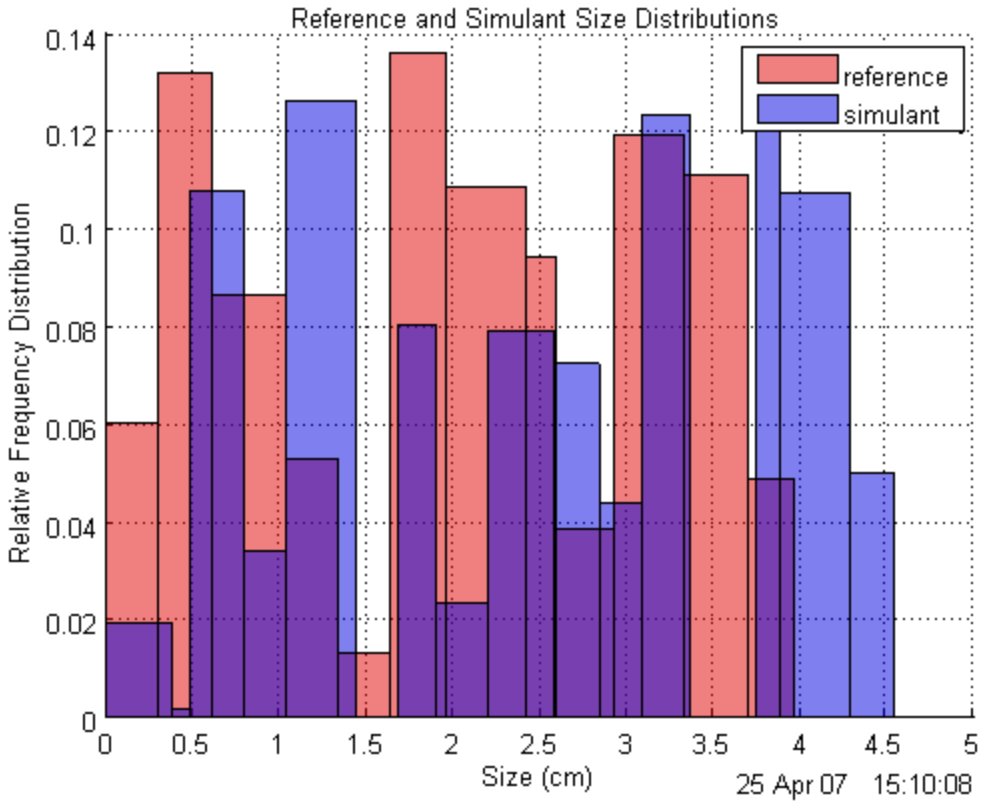
$$FoM = \begin{cases} FoM_{before\ constraints} & if \quad \left|RFD_{reference} - RDF_{simulant}\right| \le max\ RFD\ difference \\ 0 & otherwise \end{cases}$$





Size Distribution FoM

Histogram of relative frequency as a function of size



Shape Distribution FoM

- The FoM for a given reference and simulant relative frequency distributions is defined as 1 minus the square root of the integral of the weighted difference of the RFDs squared divided by the sum of the weighted integrals of the squares of the individual RFDs (Reference ISO DIS 9276-6, Representation of results of particle size analysis -- Part 6: Descriptive and quantitative representation of particle shape and morphology).

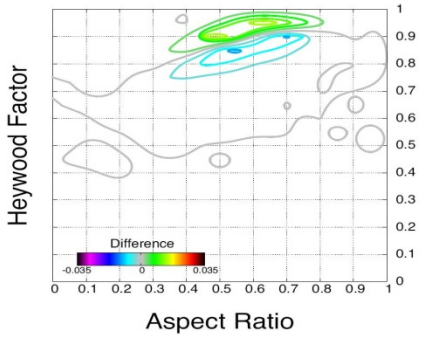
$$FoM_{before\ constraints} = 1 - \frac{\sqrt{\int w\left(RFD_{reference} - RDF_{simulant}\right)^2}}{\sqrt{\int w\,RFD^2_{reference} + \int w\,RFD^2_{simulant}}}$$

- The FoM is further subject to certain maximum error constraints:

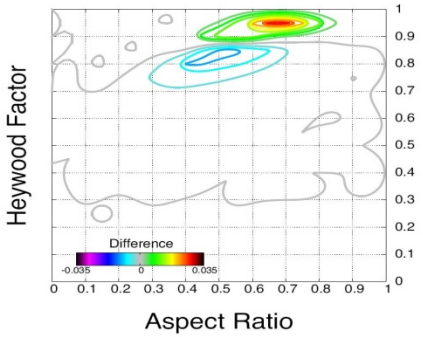
$$FoM = \begin{cases} FoM_{before\ constraints} & if \quad \left|RFD_{reference} - RDF_{simulant}\right| \le max\ RFD\ difference \\ 0 & otherwise \end{cases}$$

Shape Distribution FoM

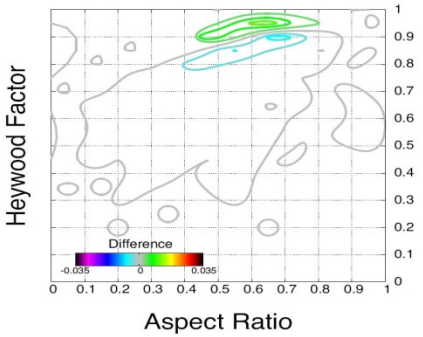
JSC-1A minus BP-1



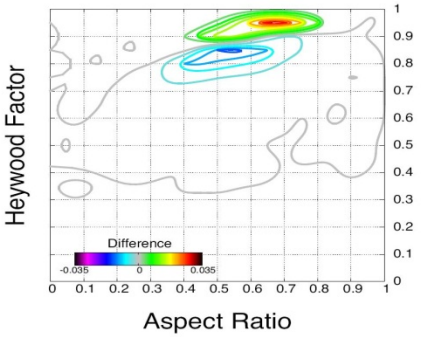
JSC-1A minus Chenobi



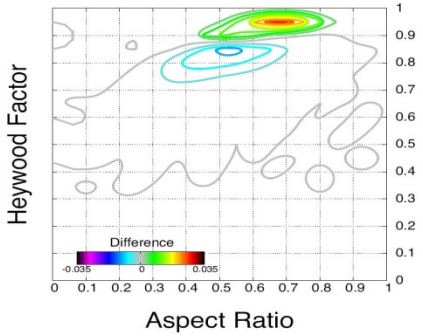
JSC-1A minus FJS-1



JSC-1A minus NU-LHT-2M



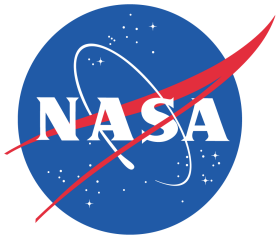
JSC-1A minus OB-1

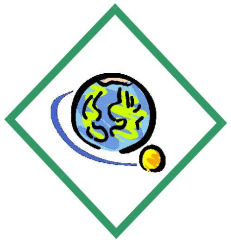


Density

- Density refers to the average weight per unit volume of a material.

- Density shall be measured by taking a sufficiently large enough sample so that the sample follows the particle size distribution of the material as defined in the slides on Size Distribution.
  - This avoids biasing the value of the density to the density of an aggregate of small particles which may pack more closely or an aggregate of large particles which may pack more loosely than an aggregate of particles which follows the particle size distribution as defined in the slides on Size Distribution.



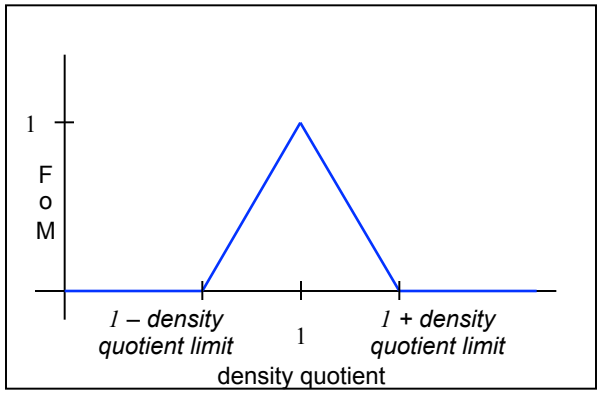


Density FoM

- The figure of merit for how closely a simulant matches a reference is proportional to the ratio of the densities.

- Ratios of less than $1 - \textit{density quotient limit}$ or greater than $1 + \textit{density quotient limit}$ correspond to figures of merit of 0, while a ratio of 1 corresponds to a figure of merit of 1.
- Mathematically and graphically this may be expressed as:

$$FoM = \begin{cases} \dfrac{1}{\textit{density quotient limit}}\left(\dfrac{\textit{simulant density}}{\textit{reference density}}\right) + \dfrac{\textit{density limit} - 1}{\textit{density quotient limit}} \\ \quad \textit{for } 1 - \textit{density quotient limit} \le \dfrac{\textit{simulant density}}{\textit{reference density}} < 1 \\ \dfrac{-1}{\textit{density quotient limit}}\left(\dfrac{\textit{simulant density}}{\textit{reference density}}\right) + \dfrac{\textit{density limit} + 1}{\textit{density quotient limit}} \\ \quad \textit{for } 1 \le \dfrac{\textit{simulant density}}{\textit{reference density}} < 1 + \textit{density quotient limit} \\ 0 \quad \textit{otherwise} \end{cases}$$

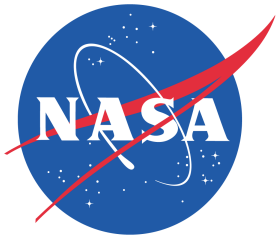


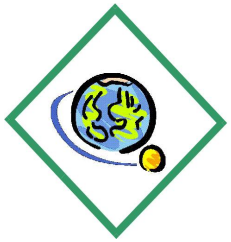
Possible Uses of ISO 10788

- Lunar Simulant Users Guide (NASA/TM-2010-216446)

  Table 3. Results of FoM composition analysis. FoM Revision 1 algorithm used with lunar reference material 64001/64002.

Simulant	**64001/64002 Reference**
NU-LHT-1M	0.65
NU-LHT-2M	0.55
OB-1	0.28
JSC-1	0.33
JSC-1A	0.35
JSC-1AF	0.43
MLS-1	0.35
FJS-1	0.36





Possible Uses of FoMs

- Lunar Simulant Users Guide (NASA/ TM-2010-216446)

Table 7. Simulant fit-to-use matrix for excavation/flow, drilling, and abrasion/wear.

- Excavation/Flow
- Drilling
- Abrasion/Wear

Table 8. Simulant fit-to-use matrix for O production and human health studies.

Questions?