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ON THE CHOICE OF LSST FLUX UNITS (*** DRAFT ***)

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ABSTRACT

A linear measure of flux is preferred for LSST catalogs. This document provides some technical detail about this issue and proposes to adopt nano-Jansky (1 nJy = 10^{-35} $\mathrm{Wm^{-2}Hz^{-1}}$) as the standard LSST flux unit. Difficulties associated with homogenizing broad-band flux measurements to a uniform system are also discussed in some detail.

1. INTRODUCTION

A linear measure of flux, not logarithmic magnitude scale, is preferred for LSST catalogs (e.g. forced fluxes can be negative due to stochastic background fluctuations). LSST flux measurements will be obtained using time-dependent and focal plane position-dependent broad photometric bandpasses. As a crucial undesired consequence of these bandpass variations and the broadness of the bandpasses, even intrinsically constant sources may display flux variability at the level exceeding LSST's photometric precision and accuracy requirements.

At the precision level of these requirements ($\sim 1\%$), it is indeed *mathematically impossible* to define a natural LSST photometric system (or natural magnitudes): in order to homogenize broad-band flux measurements to a uniform system, *assumptions about the shapes of the source spectral energy distribution must be made!*

These fundamental issues are often conflated with discussions of differences between AB and Vega photometric systems, and choices of magnitudes vs. linear fluxes, sometimes yielding confusing statements. This document aims to clarify some of the ensuing confusion by summarizing most important technical details regarding interpretation of broad-band photometry and systematic uncertainties in photometric calibration. It also proposes to adopt nano-Jansky as the standard LSST flux unit.

Relevant technical discussion is provided in §2. Readers familiar with broad-band photometry and photometric calibration can skip directly to §3, where the proposal for adopting nano-Jansky as the LSST flux unit is discussed and summarized.

2. WHAT FLUX WILL LSST MEASURE?

The complexity of the interpretation of measured and calibrated flux depends on the required flux precision and accuracy, as well as the width of the photometric bandpass. Were the photometric bandpasses infinitely narrow, or if the precision and accuracy requirements could be relaxed by a factor of a few, much of discussion presented in this document would be moot.

In this Section we review definitions of the basic quantities and briefly discuss some of the consequences of the broad photometric bandpasses. A more detailed discussion is available in the LSST document LSE-180 (Level 2 Photometric Calibration for the LSST Survey).

2.1. *CCDs count photons*

CCDs don't measure energy flux - CCDs count photons over some wavelength range set by the overall atmosphere plus system throughput, $S_b(\lambda)$ (defined as the probability that a photon with wavelength λ, or frequency $\nu = c/\lambda$, will be transmitted through Earth's atmosphere and through the observing apparatus, and converted into an electron, including the effects of both optics, sensors and all other potential losses). This quantity is *not* defined per unit energy, or per unit wavelength (or frequency): it is simply a dimensionless probability – a number between 0 and 1.

Given a flux of photons per unit time, area and frequency interval, N_ν, the source counts, C_b (in ADU), are proportional to

$$C_b \propto \int N_\nu(\nu)\, S_b(\nu)\, d\nu, \tag{1}$$

with the constant of proportionality increasing with effective collecting area and exposure time (index b stands for "bandpass"). The fact that CCDs count photons is reflected in the integration of the photon flux, N_ν; in case of a calorimeter, for example, energy flux (i.e. the specific flux, see the next subsection) would be integrated.

The integration in eq. 1 is over frequency ν because the photon flux N_ν is expressed per unit frequency. However, the running variable can be either ν or λ, and the choice of λ is more convenient in this context. It is easy to show, using $|d\nu/\nu| = |d\lambda/\lambda|$ (which follows from $\nu\lambda = c$), that an equivalent form of eq. 1 is

$$C_b \propto \int N_\nu(\lambda)\, S_b(\lambda)\, \lambda^{-2}\, d\lambda. \tag{2}$$

CCDs count photons but (unfortunately) don't record the photons' wavelength/frequency/energy. Nevertheless, it is possible to relate (calibrate) the measured source counts to energy flux – though with a few important caveats, as described below. It is important to emphasize, however, that the main source of complexity for LSST photometry is the combination of its required exquisite precision and substantial photometric bandpass width, rather than the fact that CCDs count photons. If LSST used a calorimeter device instead, the problems of measurement homogenization to account for varying bandpass would persist.

2.2. *Definition of the specific flux*

Let us first define F_ν: the specific flux (flux per unit frequency, ν) of an object *at the top* of Earth's atmosphere. The SI units for F_ν are W m^{-2} Hz^{-1} (= 10^3 erg cm^{-2} s^{-1}). Because astronomical fluxes are small, the IAU defined in 1973 a more convenient unit[1], Jansky (Jy):

$$1\,\mathrm{Jy} = 10^{-26}\ \mathrm{Wm^{-2}Hz^{-1}}. \quad (3)$$

The specific flux can also be defined per unit wavelength, F_λ, using energy conservation $F_\nu|d\nu| = F_\lambda|d\lambda|$ and $\lambda\nu = c$. The choice of F_ν, as opposed to F_λ, makes the flux conversion to the AB magnitude scale (see below) more transparent, but otherwise is completely arbitrary. Similarly, the running variable can be either λ or ν, and the choice of λ is more convenient.

2.3. *From counts to the specific flux*

The flux of photons, N_ν (s^{-1} m^{-2} Hz^{-1}), is related to the specific flux F_ν as

$$F_\nu = h\nu \times N_\nu, \quad (4)$$

where $h\nu$ is the energy of a single photon with frequency ν. Therefore, eq. 2 can be rewritten as

$$C_b \propto \int F_\nu(\lambda)\, S_b(\lambda)\, \lambda^{-1}\, d\lambda. \quad (5)$$

If instead of CCDs which measure N_ν, LSST used a calorimeter device that measures F_ν, eq. 5 would have a λ^{-2} term instead of λ^{-1}. Again, most calibration difficulties are not due to the fact that CCDs count photons but come from the fact that $S_b(\lambda)$ is a broad function, it is variable, and the shape of source spectral energy distribution is not known a priori.

2.4. *Astronomical magnitudes*

Counts C_b have to be calibrated to be useful for science. Ideally, the reported flux measurements of a non-variable source should be constant, up to random noise. For illustration, the three most common use cases are

1. How can we produce the crispest possible color-magnitude and color-color diagrams?
2. How can we best recognize a low-amplitude variable source?
3. Given a model flux $F_\nu(\lambda)$ (possibly as a function of time), how can it be best compared to measurements?

Traditional astronomical magnitudes are reported as a measurement relative to some judiciously chosen celestial calibration source (e.g., Vega),

$$m_b^{Vega} = -2.5\log_{10}\left(\frac{C_b}{C_b^{calib}}\right), \quad (6)$$

where C_b^{calib} is the counts measurement for a calibration star[2] obtained with the same system (that is, with the same $S_b(\lambda)$ up to a normalization constant) as C_b.

[1] The name honors radio astronomer Karl Jansky. Papers about the 3^{rd} Cambridge catalog of quasars published in 1950's already used 10^{-26} Wm^{-2}Hz^{-1} as a standard flux unit (without calling it Jansky).

[2] In practice, as opposed to this formal definition, multiple stars are used to derive the calibration zeropoint, and the measurement noise is taken into account as well.

The throughput $S_b(\lambda)$ cannot be assumed constant because of varying observing conditions (even if the system and Earth's atmosphere are assumed constant in time, $S_b(\lambda)$ will depend on airmass). As $S_b(\lambda)$ varies, m_b^{Vega} would vary too (beyond random measurement noise) even for a non-variable source (unless it has exactly the same spectral energy distribution as the calibration source)!

This clearly undesireable effect is in practice corrected for using the so-called "color terms". Therefore, eq. 6 is deceivingly simple and the need to *assume* the shape of the source's spectral energy distribution, as discussed below, *cannot be avoided*. Further details can be found in LSE-180 (see Section 4.1).

2.5. *Definition of broad-band flux*

As discussed in the LSST Science Requirements Document (Section 3.3.4), "LSST is a broad-band photometric system and will deliver calibrated in-band flux, F_b, defined by

$$F_b = \int F_\nu(\lambda)\phi_b(\lambda)d\lambda, \quad (7)$$

where $F_\nu(\lambda)$ is the specific flux of an object *at the top* of the atmosphere, and $\phi_b(\lambda)$ is the normalized system response for the given band." This expression follows directly from eq. 5. The calibration of measured C_b to obtain F_b is addressed further below.

The normalized system response is defined by

$$\phi_b(\lambda) = \frac{S_b(\lambda)\lambda^{-1}}{\int S_b(\lambda)\lambda^{-1}d\lambda}. \quad (8)$$

where $S_b(\lambda)$ is the overall atmosphere + system throughput. It is defined by

$$S_b(\lambda) = S_b^{sys}(\lambda) \times S_b^{atm}(\lambda), \quad (9)$$

where $S_b^{atm}(\lambda)$ is the *probability* that a photon with wavelength λ will be transmitted through the atmosphere, and $S_b^{sys}(\lambda)$ is the probability that the transmitted photon will be converted into an electron by the system (optics, CCDs). Again, these quantities are dimensionless probabilities (numbers between 0 and 1).

As discussed above, the λ^{-1} factor in eq. 8 reflects the fact that CCDs are photon-counting devices: it comes from the conversion of energy per unit frequency into the number of photons per unit wavelength. If a calorimeter was used instead, λ^{-1} term would turn into λ^{-2} but all the problems caused by integration over the broad bandpass would remain.

Note that the product $\phi_b(\lambda)d\lambda$ is dimensionless; it acts in eq. 7 as a dimensionless weighting function and the unit for F_b is *same* as for F_ν (by construction). In other words, eq. 7 doesn't represent "integration under the F_ν curve" – instead, F_b is a "weighted average" of F_ν. While details of the "weighting function" $\phi_b(\lambda)$ depend on the device properties, the fact that F_ν is a "weighted" quantity is purely a consequence of the broad bandpass. Note that only in the case of an infinitely narrow bandpass, the measured quantity would really be the specific flux F_ν at some well defined wavelength.

Had we chosen to use F_λ instead of F_ν, an analog to eq. 7 would have been

$$F_b^* = \int F_\lambda(\lambda)\phi_b^*(\lambda)d\lambda, \tag{10}$$

where

$$\phi_b^*(\lambda) = \frac{S_b(\lambda)\lambda}{\int S_b(\lambda)\lambda d\lambda}. \tag{11}$$

In this case, the calibrated flux F_b^* has the same units as F_λ, and the weighting factor $\phi_b^*(\lambda)d\lambda$ is now skewed more towards the red edge of the bandpass, compared to $\phi_b(\lambda)d\lambda$. Of course, C_b is same in both cases - it is only our (arbitrary) choice of flux calibration that distinguishes F_b and F_b^*. The only practical implication of the choice between F_b and F_b^* is the type of the spectral energy distribution for which photometric standardization correction for bandpass variation (see eq. 13) vanishes.

2.6. *The curse of broad-band flux*

There are a few consequences of the finite width of $\phi_b(\lambda)$ that need to be (re)emphasized (and are *not* the result of the specific choice for flux calibration).

Even for a temporally non-variable $F_\nu(\lambda)$, F_b will vary if $\phi_b(\lambda)$ varies (even if the atmospheric and system properties are unchanged, variation of observing airmass can change $\phi_b(\lambda)$). In order to standardize measurements to a common standard system, one in which F_b of a temporally non-variable source would not vary (modulo random noise), we need to define a *standard* normalized system response, $\phi_b^{std}(\lambda)$. In addition, we must know the *shape* of the source spectral energy distribution (SED), $f_\nu(\lambda)$, defined by

$$F_\nu(\lambda) = F_o\, f_\nu(\lambda), \tag{12}$$

where $F_\nu(\lambda_o) = F_o$ and $f_\nu(\lambda_o) = 1$ for some fiducial wavelength λ_o. Then we can compute standardized flux as

$$F_b^{std} = F_b\, \frac{\int f_\nu(\lambda)\phi_b^{std}(\lambda)d\lambda}{\int f_\nu(\lambda)\phi_b(\lambda)d\lambda}. \tag{13}$$

Traditionally, corrections to the standard system (the ratio of two integrals in eq. 13) are called *color terms*. Historically, they were obtained empirically (typically as approximating linear functions of source color and airmass) rather than by using eq. 13. Assuming main-sequence stars and standard atmosphere, plausible variations of airmass induce variations of F_b around F_b^{std} of a few percent (i.e. several times larger than the photometric precision requirements).

Without knowing, or assuming, $f_\nu(\lambda)$, it is *mathematically impossible* to standardize measurements F_b – this is the "curse" of broad-band fluxes (note that in the special case of a flat SED, $f_\nu(\lambda)$ = constant, $F_b^{std} = F_b$; had we chosen F_b^* instead of F_b, the standardization correction would vanish for $f_\nu(\lambda) = \lambda^2$, that is, for $f_\lambda(\lambda)$ = constant). This "curse" cannot be avoided whatever is the flux calibration choice (i.e. F_ν vs. F_λ); the "problem" is the finite width of the photometric bandpass.

2.7. *Standardized fluxes*

For each flux measurement, LSST will report both F_b and ϕ_b (with $\phi_b^{std}(\lambda)$ pre-defined and always known). There is also need to report standardized flux computed using eq. 13 (e.g. to help users construct color-color and color-magnitude diagrams, or to search for variable sources). There are at least two options for choosing $f_\nu(\lambda)$: i) assume a flat SED ($F_b^{std} = F_b$, i.e. effectively no correction is applied), and ii) assume the best possible estimate of object's SED, using available LSST color measurements and possibly other information.

Neither choice is perfect: the first choice, while simple, does not account for the variation of F_b around F_b^{std} due to changes of ϕ_b (except in case of flat SED), while the second choice can be grossly incorrect (e.g. when SED type is incorrectly chosen, such as stellar SED instead of quasar or supernova SED). Therefore, it is important to enable users i) to undo whatever default flux standardization correction was used, and ii) to easily re-do the computation with a different choice of the spectral energy distribution (e.g. for multiple hypothesis testing, such as distinguishing "star", "quasar", and "supernova" SEDs, or galaxy SEDs of different intrinsic types and at different redshift). The current baseline LSST plan is option ii).

2.8. *Some pitfalls when interpreting measured fluxes*

When comparing a model for the specific flux, $F_\nu^{model}(\lambda)$, to measurements F_b, the proper way to proceed is to compute the model prediction for F_b using eq. 7

$$F_b^{model} = \int F_\nu^{model}(\lambda)\phi_b(\lambda)d\lambda, \tag{14}$$

and then compare F_b^{model} to measurement F_b. When measurements F_b have already been standardized as F_b^{std}, this data vs. model comparison (e.g. photometric redshift estimation) can suffer from systematic errors when SED shape, $f_\nu(\lambda)$, assumed for flux standardization differs from the shape of $F_\nu^{model}(\lambda)$, *even when* $\phi_b(\lambda)$ was substituted by $\phi_b^{std}(\lambda)$.

Flux measurements (F_b or F_b^{std}) are often interpreted as corresponding to $F_\nu(\lambda_{eff})$, at some effective wavelength, λ_{eff}, and compared to model flux $F_\nu^{model}(\lambda_{eff})$. This practice usually results in systematic errors because λ_{eff} is a function of $f_\nu(\lambda)$, and thus there is no universal value of λ_{eff} applicable to all sources.

2.9. *Calibration of counts to get fluxes*

Image processing pipelines, more precisely object measurement pipelines/algorithms, will produce counts, C_b (together with ϕ_b). It is assumed that all the relevant instrumental and other effects had been taken into account such that the following relationship is valid

$$F_b = \alpha\, C_b, \tag{15}$$

for all sources from some judiciously chosen "calibration patch" (spatial variation of α over the patch is assumed to be corrected for, though the above equation could be easily generalized; in principle, this "calibration patch" could correspond to the entire sky if all C_b were "reduced to the same system" using self-calibration).

A set of calibration stars will be available to estimate α: for these stars we (assume that we) will know broad-band flux in an arbitrary calibration bandpass $\phi_{calib}(\lambda)$

(e.g. in Gaia's bandpasses)

$$F_{calib} = \int F_\nu(\lambda)\phi_{calib}(\lambda)d\lambda. \tag{16}$$

We also assume that we will have a good knowledge of the SED shape, $f_\nu(\lambda)$ for calibration stars. The implied fluxes of calibration stars corresponding to bandpass b, F_b^{calib} can then be computed analogously to eq. 13, using $\phi_b(\lambda)$ and $\phi_{calib}(\lambda)$,

$$F_b^{calib} = F_{calib} \frac{\int f_\nu(\lambda)\phi_b(\lambda)d\lambda}{\int f_\nu(\lambda)\phi_{calib}(\lambda)d\lambda}. \tag{17}$$

Finally, the calibration coefficient α (related to photometric zeropoint when working in magnitude space) is computed from

$$F_b^{calib} = \alpha\, C_b^{calib}, \tag{18}$$

by the usual least squares minimization, or perhaps using a more robust statistical method.

2.10. *AB magnitudes*

The in-band flux in astronomy is often reported on a magnitude scale, and LSST has adopted AB magnitudes defined as

$$m_b^{AB} = -2.5\log_{10}\left(\frac{F_b}{F_{AB}}\right). \tag{19}$$

where $F_{AB} = 3631$ Jy. The same expression applies to F_b^{std}, or any other flux. The choice of normalization flux F_{AB} results in correspondence between AB magnitudes and Vega magnitudes in the Johnson's V band (i.e. approximately, 3631 Jy is the flux of Vega in the standard V band).

2.11. *Relationship between AB magnitudes and Vega magnitudes*

It follows from eqs. 6 and 18 that $F_b/F_b^{calib} = C_b/C_b^{calib}$ and

$$m_b^{Vega} = -2.5\log_{10}\left(\frac{F_b}{F_b^{calib}}\right). \tag{20}$$

When F_b^{calib} is available (e.g. Vega's flux of 3631 Jy in the V band), transformations between m_b^{AB} and m_b^{Vega} are straightforward and effectively there is no practical difference between the approaches. When F_b^{calib} is unavailable, m_b^{Vega} are simply relative flux measurements and cannot be transformed to an absolute flux scale implied by AB magnitudes.

3. THE CHOICE OF FLUX UNIT

Most astronomical surveys, especially space-based surveys and surveys at wavelengths other than optical, used Jansky as the flux unit. One notable exception is SDSS, which used maggies (see Appendix A). There appears to be no advantage for LSST to adopt maggies over Jansky, and for consistency with the practice adopted by numerous other astronomical catalogs, it seems better to adopt Jansky.

3.1. *Jansky as the preferred flux unit for LSST*

There is fundamentally no difference between the flux measurements discussed here and any other physical measurement that is subject to random and systematic uncertainties. It is rather common to report both types of measurement uncertainties in physical sciences. Indeed, the LSST Science Requirements Document (Section 3.3.4) explicitly addresses the issue of systematic uncertainties in photometry and introduces the separation of "internal absolute" calibration accuracy from "external absolute" calibration accuracy and from the offset from the overall flux scale. The deviation of the LSST system from a perfect AB system (that is, the systematic error in calibrating the flux scale to correspond to Jansky) Δ_b, is expressed relative to the fiducial band (chosen to be the r band) as

$$\Delta_b = \Delta_r + \Delta_{br}, \tag{21}$$

(eq. 9 from the SRD), where Δ_r describes overall systematic uncertainty in the LSST flux scale calibration (a single number for the whole survey). The "band-to-band zeropoint errors" Δ_{br} are thus decoupled from the overall "gray scale" offset Δ_r, which minimizes error covariances. Similarly to SDSS, a variety of methods will be used to assess likely values of Δ_{br} and Δ_r for each LSST Data Release.

3.2. *Summary*

In summary, it is proposed here to calibrate LSST fluxes to a physical scale (e.g. using Gaia catalogs), adopt nano-Jansky (nJy) as the LSST flux unit, and report the best available estimates of Δ_{br} and Δ_r with each LSST Data Release. In particular, Δ_r will describe the systematic flux uncertainty – the discrepancy between an ideal flux scale in Jansky and "Jansky" scale reported by LSST.

For the faint fluxes probed by LSST, a more convenient unit is nano-Jansky (nJy). The AB magnitude values of 27.5 (fiducial coadded image depth) and 24.5 (fiducial single-image depth) correspond to 36.3 nJy and 575 nJy.

Lastly, it will need to be strongly emphasized to the users that LSST measurements are fundamentally broadband fluxes, and not "a flux-at-a-wavelength", despite using the unit for the specific flux. In addition, sufficient information will have to be provided in data products (catalogs and documentation) so that the entire calibration process from source counts in ADU to fluxes in nano-Jansky can be easily understood and back-engineered if desired.

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APPENDIX

A. THE CURIOUS CASE OF MAGGIES

In analogy with eqs. 6 and 19, magnitudes can be defined[3] as

$$m \equiv -2.5 \log_{10} (\text{maggie}) , \tag{A1}$$

where "maggie" is the source flux expressed in some arbitrary units,

$$\text{maggie} \equiv \frac{F_b}{F_o}. \tag{A2}$$

In case of AB magnitudes, eq. 19 implies that maggie is flux measured in units of 3631 Jy,

$$\text{maggie} = \frac{\text{flux (Jy)}}{3631\,\text{Jy}}. \tag{A3}$$

In practice (e.g. SDSS), a more convenient quantity is nano-maggie, which is flux measured in units of 3631 nJy.

In case of traditional magnitudes (see §2.4), maggies are a relative flux measure

$$\text{maggie} \equiv \frac{C_b}{C_b^{calib}} = \frac{F_b}{F_b^{calib}}. \tag{A4}$$

Maggies were introduced as an alternative flux unit in order to emphasize that zeropoints for astronomical flux calibration change often – and presumably much more often than the actual counts measurement. Such was the case of SDSS, where the sky was imaged essentially once and with a precision better then the accuracy of calibration photometry (i.e. at the bright end systematic photometric uncertainties were larger than random uncertainties). It was anticipated that photometric zeropoints would eventually improve and the dataset recalibrated. But it needs to be noted that fluxes also change when other aspects of calibration change (non-linearity and cross-talk corrections, flatfields, standard apertures, point-spread function, etc.) – photometric zeropoints are only one of many calibration factors. Indeed, it turned out that in practice most SDSS users would simply convert maggies to AB magnitudes (by assuming that F_o from eq. A2 is 3631 Jy), and thus implicitly to Jansky (and sometimes explicitly, e.g., when constructing multi-wavelength spectral energy distributions). SDSS Project curates a list of five best estimates of the systematic flux errors in the *ugriz* bands introduced by this conversion. These errors are analogous to quantities Δ_b discussed in Section 3.1.

It is sometimes claimed that maggies have the benefit of not pretending to exactly correspond to physical units (Jy). This somewhat philosophical advantage was not born in practice because of the immediate users' conversion to AB magnitudes mentioned above.

B. DISCUSSION

The following few points that often came up in previous discussions are worth reiterating:

1. There isn't that much difference between using Jansky and maggies (when expressed on an absolute flux scale): the key decision is to report physical flux on a linear scale.

2. Irrespective of which flux unit is chosen, the changes of the photometric calibration zeropoints will affect whatever is reported, whether it is maggie, mag^{AB}, mag^{Vega}, or nJy, as long as it is implied that physical flux is reported. Only if truly relative measures of flux are reported (e.g. with respect to Vega, but without knowing what calibrated Vega fluxes really are), will magnitudes (but not fluxes in maggies or nJy) stay unchanged. However, in this case rather ugly details are hidden (e.g., how exactly was the relative flux calibrated and how stable is the flux scale), and in the context of sub-1% photometry this case appears to be of historical interest only. After all, LSST SRD mandates that reported fluxes are calibrated on an absolute flux scale.

3. "But: we are measuring broad-band flux, and not the specific flux!" Well, yes, this is an unfortunate fact. However, it is not relevant for the maggie vs. Jy discussion. It is impossible (mathematically!) to relate these two flux measures without knowing the source SED, whether we use relative or absolute flux calibration and magnitudes, maggies or Jy!

4. Once an estimate of the source SED is available or assumed, the transformation from the broad-band flux to the specific flux is dimensionless and thus obviously independent of the choice for flux units and relative vs. absolute calibration choice (again, the broad band flux vs. the specific flux issues do not provide arguments for maggie vs. Jy discussion).

[3] See https://www.sdss3.org/dr8/algorithms/magnitudes.php