Simplifying Pyrometer Selection with Signal to Noise Ratio

Abstract

Selection and comparison of pyrometers can be simplified by the use of signal-to-noise ratio (SNR). Typically pyrometer performance is evaluated looking at individual specifications for speed, resolution, accuracy, repeatability, spot size etc. The risk in comparing these individual specifications is that there are tradeoff dependencies between them (e.g. between speed and resolution). All of these performance specifications ultimately stem from instrument design and the resultant instrument's SNR capability; SNR is an integrated measurement of a pyrometer's inherent sensitivity, dynamic range, and overall performance.

Introduction

Anyone who has tried to purchase a pyrometer knows how complicated the process can be. First there are multiple parameters like wavelength, temperature range, speed, accuracy, etc. that must be selected and matched to the object whose temperature is to be measured. On top of this, comes the task of comparing pyrometer specifications from different manufacturers each with a different mix and match of performance specifications. Complicating this further is the difference in terminology used by one manufacturer to another. One manufacturer's "resolution" may be another's "precision". "Accuracy" is often confused for "repeatability". Then if this isn't enough, there is the hype surrounding emissivity compensation and the fine print associated with exactly what is defined by the specification on the manufacturer's product data sheet.

Sometimes it seems that buying a pyrometer is more like buying a used car than a scientific instrument. Why is this?

The main source of confusion seems to be rooted in the multiple tradeoff dependencies between pyrometer performance specifications (see Figure 1). For example, pyrometer speed is not independent of resolution. Accuracy is not independent of repeatability but at the same time is a different entity.

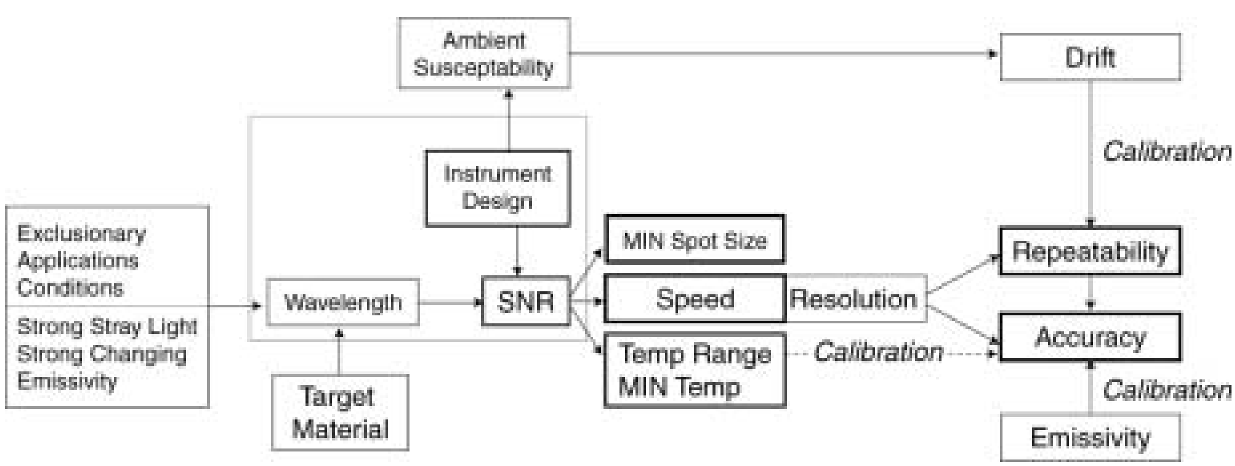

Figure 1: Inter-relationships between pyrometer performance specifications

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3033 Scott Blvd. Santa Clara, CA 95054
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Fortunately, there is one specification – signal-to-noise ratio (SNR) – that can simplify evaluation. SNR stems from the inherent physics of the pyrometer detector's wavelength and the actual design of the instrument. Because of this, it bounds the instrument's performance in speed, dynamic range, resolution, accuracy, repeatability, and spot size including the tradeoffs therein.

Basic Pyrometer Design

To see how SNR works, let's look at how pyrometer's are constructed (see Figure 2).

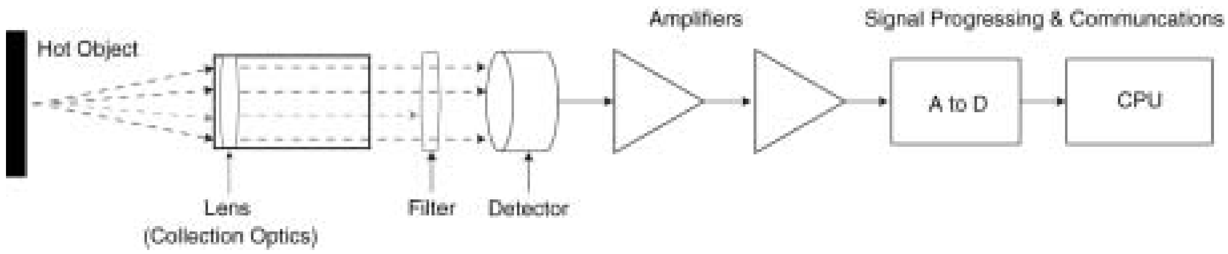


Figure 2: Pyrometer system block diagram

All pyrometers have some form of light collection optics, to capture the thermal radiation from the target object to be measured and transmit this to the detector. The collected light first passes through a filter, tuned to the detector's wavelength. The actual design of the optical path, including proper focal length, is critical and directly affects collection efficiency. A properly designed, high efficiency optical system maximizes the number of photons reaching the detector, improving the signal-to-noise seen by the detector. The detector converts the light energy into an electrical signal, which goes through various amplification steps. The amplified analog signal is digitized and the digital signal processed via an algorithm to yield an output temperature measurement.

Referring to Figure 1, signal and noise come from four source classes:

- The object to be measured: This determines the technical feasibility of whether the object can be measured or not via pyrometry. Aside from feasibility, this sets the required detector wavelength, the first fundamental restriction on the instrument.
- The instrument design: The degree to which the pyrometer is able to approach the theoretically measurable result is dependent on how well all the design elements are put together. Obviously, a key objective of pyrometer design is to maximize the SNR.
- Ambient light interference: Unwanted signal in the form of stray light seen by the detector.
- Environmental susceptibility: Noise caused by environmentally induced drift of the instrument electronics (e.g. temperature) or EMI.

Definition of Key Terms

Accuracy: Measured agreement with national standards

Drift: Long term repeatability. Usually electronics and/or environment related

Interference: Extraneous “unwanted” signal from sources other than the hot object to be measured.

Noise: Statistical measure of precision associated with detector performance (1σ variation in signal).

Signal: Measurement of detector response when viewing a hot object

SNR: Ratio specified in decibels (dB) of signal divided by noise.

Speed (Data Rate): Frequency of measurement sampling usually specified per second (Hz)

Resolution (Precision): Smallest meaningful measurement increment.

Repeatability (Stability): Measured as 1σ variation about a the mean temperature. Always dependent on data rate

Selecting a Pyrometer Step One: Determine Application Feasibility

The first step in selecting a pyrometer is determining whether the object to be measured and associated application conditions are such that pyrometry can be used. This means the signal from the source object must be high enough and of the correct character that the instrument can detect it.

Conditions that make this difficult and may bar any form of pyrometric measurement:

Low temperature gradient vs. background thermal emission (stray light) – Pyrometers operate on the principle that the object to be measured emits thermal energy at some wavelength in sufficient quantity to be detected in accordance with Planck's Law (see Figure 3). However if the object's thermal emission (signal) is too low relative to the background thermal emission (interference), the instrument will be unable to distinguish between the two. The use of longer wavelengths (>1.5µm) can mitigate this but at the expense of sensitivity. Pyrometer filtering is also aimed at reducing this. Supplemental light shields and baffles can be employed as well.

Strongly changing emissivities – Temperature reading via radiation thermometry makes certain assumptions about emissivity (see Figure 4). Fluctuations in emissivity can cause the reported temperature to be inaccurate (e.g. during deposition of optical thin film or dielectric coatings). The selection of a shorter wavelength (<1.0µm) pyrometer can partially mitigate this impact.

Very small spot size – May result in insufficient signal reaching the detector (i.e. small spot means less light).

Sharp spikes in temperature – Instrument may have insufficient resolution at speed to keep up with the change in temperature (e.g. flash anneal).

Film deposits on chamber windows – In many applications, the pyrometer is mounted outside a process chamber and views the hot object through an optical port. Hazing of the window due to material deposition or etching can obstruct the signal.

All of these conditions can be compensated for to some degree. However if your application involves any of

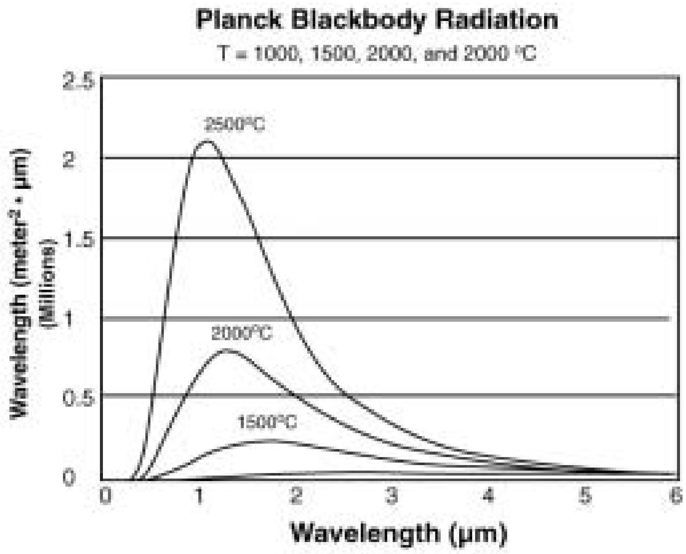


Figure 3: Blackbody radiation spectra

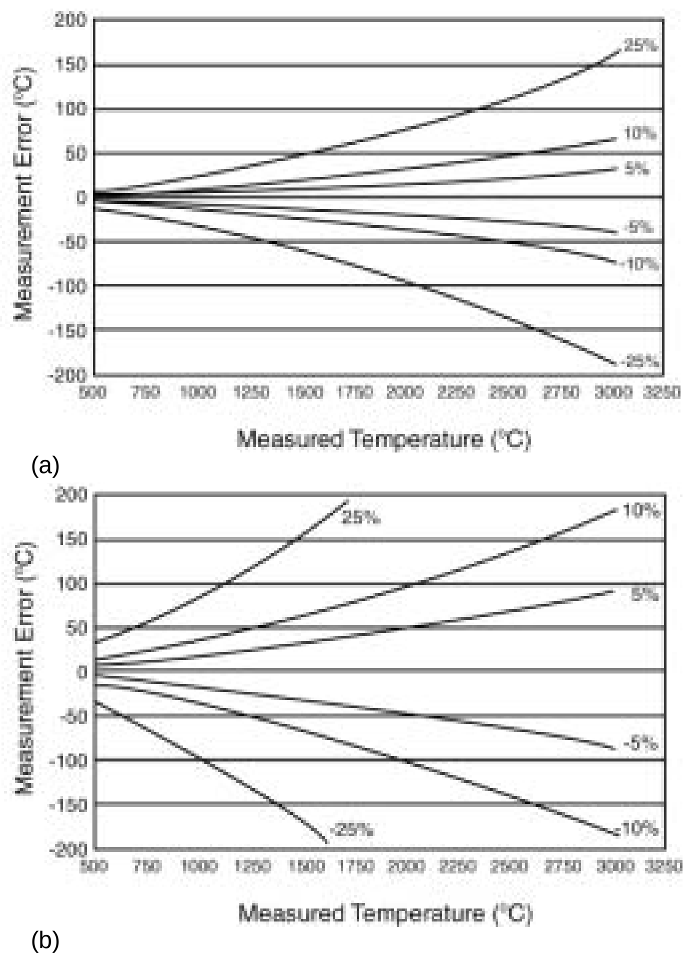


Figure 4: Temperature measurement error as a function of emissivity at (a) short wavelength, 0.95µm and (b) long wavelengths, 3.5µm.

these, it usually requires consultation with a manufacturer's engineering staff and development of a customized solution.

Selecting a Pyrometer Step Two: Select the Correct Wavelength

If these conditions cannot be suitably compensated for or are absent, the next step in selecting a pyrometer is choosing the correct wavelength.

The main factors affecting this choice:

Target material – Materials may have light transmittance spectra that dictate selection of specific wavelengths (e.g. silicon is transparent at wavelengths longer than 1µm and therefore requires the use of a shorter wavelength pyrometer). A wavelength should be selected where the object is opaque.

Stray room light immunity – Most stray light interference comes from room light with spectra in the near-IR and visible range. Longer wavelength pyrometers are less susceptible to this room light interference because these operate beyond the visible spectrum. They can also measure lower temperatures because there is more radiation of longer wavelength available at lower temperatures (see Figure 3). However there is a tradeoff. Longer wavelength pyrometers are more susceptible to larger measurement error caused by errors in emissivity, resulting in reduced accuracy, resolution and limiting dynamic temperature range.

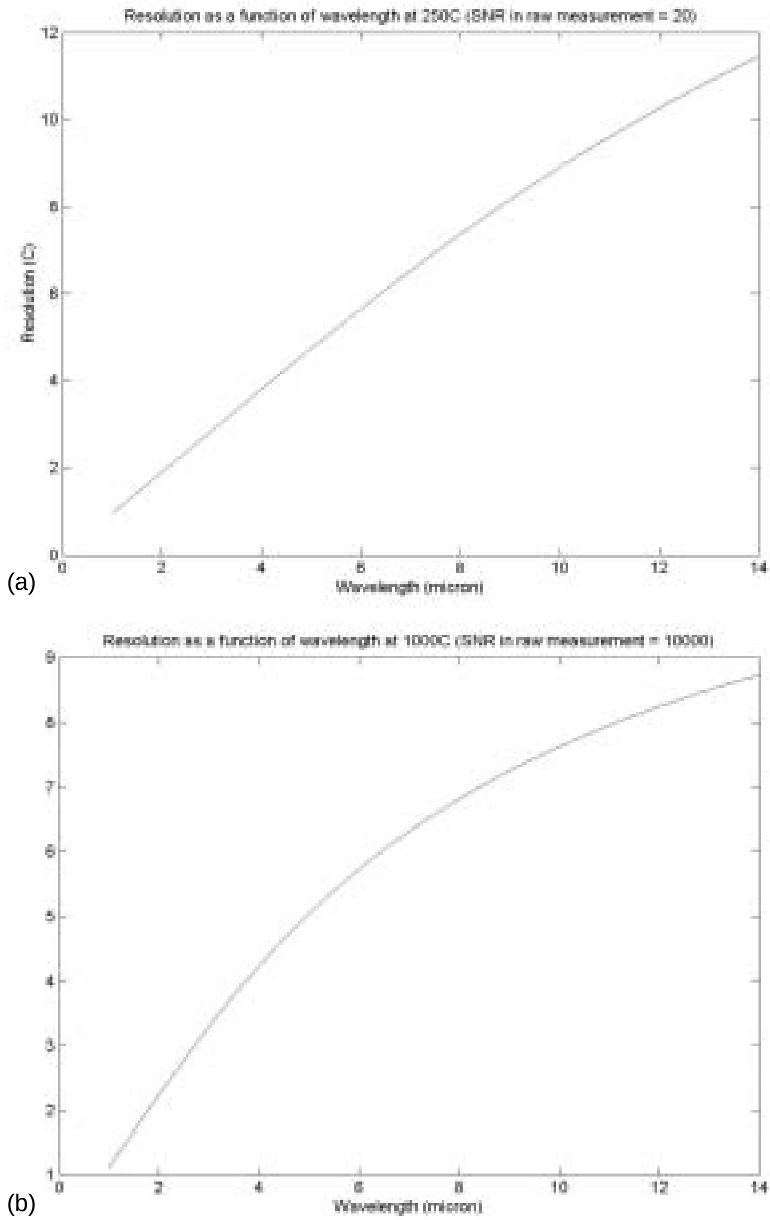


Figure 5: Resolution as a function of wavelength at (a) 250°C and (b) 1000°C, each assuming an equal SNR in raw measurement.

(Note: longer wavelength pyrometers are not less susceptible to stray thermal radiation from other heat sources in proximity to the hot target object.)

Measurement sensitivity (SNR) – Shorter wavelength pyrometers are more sensitive and capable of higher resolution, higher accuracy measurements (see Figures 5). At higher temperatures, the SNR in raw measurement for longer wavelengths is worse than that for the shorter wavelengths. The assumption of equal SNR in raw measurement is not valid, and the actual performance of longer wavelength instrumentation can be much worse.

Cost – Shorter wavelength pyrometers are generally more expensive than longer wavelength units due to the detectors and the more complex signal processing requirements and subsequent electronics.

The wavelength selected determines the maximum achievable SNR (physics limited). The effective instrument SNR is a function of instrument design. Table 1 summarizes wavelength selection tradeoffs.

One of the objectives of pyrometer design is to maximize the effective SNR of the instrument. Key design elements affecting instrument SNR:

Collection optics – Must be designed to collect the maximum number of photons for a given spot size at the desired focal distance.

Transmission optics – Designed to maximize the transmission of the collected light to the detector, sometimes via fiber optic cable. This is done by minimizing light loss through proper selection of fiber material, minimizing or preferably eliminating connectors, minimizing cable lengths and bending of cables.

Tradeoffs	Short	Long
Stray Room Light Immunity	Less	Greater
Emissivity Error Immunity	Greater	Less
Lower Temperature	More Difficult	Less Dificult
Accuracy (Inherent)	Greater	Less
Resolution (Inherent)	Greater	Less
Dynamic Temprature Range	Greater	Less
Cost	Greater	Less

Table 1: Short (<1.5µm) vs. Long (>1.5µm) Wavelengths

Filter – Selected to block light of the wrong wavelength (interference) and pass through light of the proper wavelength (signal) optimum to the detector.

Detector – Designed to maximize capture of the filtered light and its conversion to electrons without introducing additional electronic noise.

Amplification – Designed to boost detector signal with minimal distortion and minimal addition of noise (i.e. boost SNR).

A/D Conversion – Designed to digitize the amplified analog signal without introducing distortion and with sufficient resolution to faithfully reproduce the analog signal.

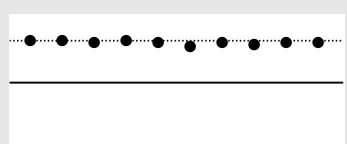
Signal processing algorithm – Designed to translate the raw digital signal into a temperature measurement via some form of algorithm with high accuracy.

A pyrometer with high SNR will be able to outperform one with a lower SNR along the following key performance specifications:

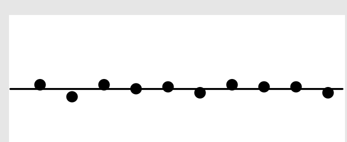
- Dynamic temperature range
- Minimum temperature
- Minimum spot size
- Speed/resolution
- Accuracy

Repeatability is Not Accuracy

What is generally more important in process control is repeatability, which is, again, different from accuracy. “Repeatability” is the ability of the pyrometer to adhere to some set point or measured point, regardless of whether that measurement is accurate or not.



Repeatable but Inaccurate



Repeatable and Accurate

Achieving high repeatability is directly related to the pyrometer’s capability to achieve fine resolution without any drift. Typically, the pyrometer will require some form of environmental temperature compensation feature and should undergo periodic calibration.

As can be expected, a higher SNR pyrometer will generally cost more than a less capable unit. Therefore, care should be taken not to over specify pyrometer performance requirements.

Selecting a Pyrometer Step Four: Evaluate Tradeoffs Between Specifications

Probably the most confusing aspect of selecting a pyrometer is understanding the tradeoffs between the different performance specifications (Figure 1). Complicating this is the tendency of many manufacturer's data sheets to state only maximum capability for each specification, without consideration of tradeoffs against other specifications. For example, specifying resolution without a corresponding output data rate (speed) is meaningless.

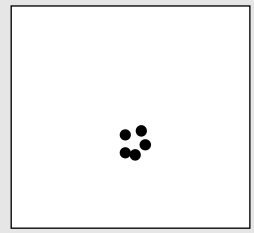
In general, the higher the pyrometer's SNR, the less restrictive the tradeoffs. But one should be aware of the main tradeoffs:

- *Output rate (speed) vs. resolution* – Typically, greater resolution can be achieved by some form of sample averaging. The higher the number of samples averaged, the higher the resolution. Unfortunately, this comes at the expense of output rate as it takes more time to collect multiple sampling points. High SNR allows faster sampling rates with less sample averaging to achieve higher resolution with less sacrifice in speed.
- *Minimum temperature or spot size vs. resolution or speed* – Because both conditions result in less signal vs. noise to reach the detector, more samples must be taken to achieve a desired resolution with consequent decrease in speed. High SNR reduces this tradeoff.
- *Temperature range vs. accuracy* – Pyrometers typically use some form of curve-fitting algorithm to convert signal to temperature. As a result, depending on the quality of the curve-fit at a given temperature point, accuracy may be higher or lower. Accuracy can be improved by narrowing the temperature range, by calibrating near the measurement of greatest interest, or by having more calibration points along the curve, all of which decrease the likelihood of curve-fit errors,

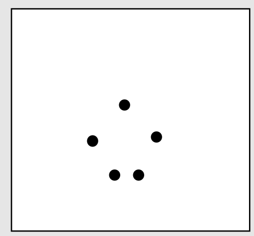
  In addition, shorter wavelength pyrometers have an inherent accuracy advantage due to the nature of the Planck curves (see Figure 3). For example, the change in signal per °C change at 1µm is three times greater than at 5µm.

Resolution is Not Accuracy

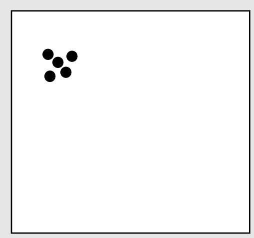
A common source of confusion is that between resolution and accuracy. They are not the same and only mildly related. "Resolution" (also commonly called "precision") defines how finely the pyrometer can represent a quantity. "Accuracy" defines how much of the measurement has value and is usually defined against some reference standard. It is possible for a measurement to be (a) high resolution yet totally inaccurate or (b) accurate yet not very precise. Resolution is more inherent in the capability of the pyrometer. Accuracy is more determined by quality of calibration and absence of drift.



Precise & Accurate



Imprecise & Accurate



Precise but Inaccurate

In scientific studies, both resolution and accuracy are important. However for process control, while resolution may be important, accuracy may not be.

Selecting a Pyrometer Step Five: Additional Selection Criteria

Two other criteria are often factors in pyrometer selection. The first is drift. The second is emissivity compensation. Whether these are important is application dependent.

- *Drift (Stability)* - Affecting both repeatability and accuracy is pyrometer drift. "Drift" is defined as change in repeatability over a period of time. Drift is mainly due to a change over time in the performance of various instrument components (e.g. electronics) and susceptibility to changes in ambient conditions. For example, many pyrometers are susceptible to change in the environmental temperature. This can be a problem in high temperature measurements where the pyrometer is placed close to the hot object being measured. If long term stability is important (e.g. in process control), select a pyrometer that has built in environmental compensation.

- *Emissivity Compensation* – Pyrometers operate in accordance with Planck's law where thermal radiation is a function of emissivity(e). To the degree which a hot object does not act as a perfect black body radiation source (e = 1), pyrometer's can yield inaccurate temperatures (Figure 4). Depending on the degree of accuracy required, this may necessitate some form of emissivity compensation. There are basically two strategies for dealing with emissivity compensation:

  If the emissivity of the hot object is not changing – This case can be handled via calibration of the pyrometer or use of a pyrometer with correction factor input capability. Active compensation is also an option but may be cost prohibitive.

  If object emissivity is subject to mild changes – Selection of a shorter wavelength pyrometer can reduce inaccuracies caused by minor changes in emissivity. Selection of a pyrometer that allows input of single or multiple correction factors along the temperature curve may also be available. An active emissivity correction method may be available with selected pyrometers, however these each have pros and cons and generally require consultation with the manufacturer.

  Note: There is a lot of hype surrounding active emissivity compensation methods. Discussion of the various schemes is beyond the scope of this paper.

Generally, the highest accuracy pyrometers will be short wavelength, high SNR units with environmental temperature drift compensation. Some form of emissivity correction may be required but must be evaluated under specific context.

Summary

Selection of a pyrometer can be fraught with difficulties if attempting to compare individual performance specifications. This is because comparisons of individual specifications fail to address tradeoffs between them. Because SNR is an inherent measure of pyrometer capability reflective of tradeoffs, it can be used to simplify comparison.

Your local Luxtron sales representative is:

3033 Scott Boulevard, Santa Clara, CA 95054-3316
408.727.1600 tel 408.727.1677 fax
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