"Internet Telescope" Performance Requirements

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Abstract

Efficient operation of an astronomical telescope over the internet by a remote user requires a high level of performance from the telescope, instruments, support facilities and the control system. The needed performance is partially determined by the focal length of the telescope, the site properties, and the remote user requirements. In this paper we develop the basic pointing, tracking, and focus requirements and discuss how they interact with the remote users of the system.

Introduction

An “Internet Telescope” allows a remote user to take command of the observatory and perform observations. Typically we are discussing **real time direct imaging** rather than photometry or spectroscopy, although most of the performance requirements are similar for the various other instruments. We are not discussing a "batch processing" mode of operation where a set of observations are submitted well in advance of when the observations are performed. In the batch mode, a scheduler establishes when the observations are performed and afterwards, the data is sent to the user.

In the real time mode, the next scheduled remote user is recognized by the scheduler at the beginning of their time slot and is allowed remote access to the telescope. The user then specifies the coordinates of the first object of interest and the telescope slews to those coordinates. This object location may be specified by entering coordinates or by using a GUI (graphical user interface).

The user then specifies how the imaging is to be performed by specifying the exposure time (integration time), the desired filter, and other camera parameters. The image is acquired and transmitted to the remote user and the next observation is performed. This sequence continues until the user's allocated time slot is completed and the next scheduled user is granted access to the observatory.

The control sequence becomes:

1. Recognizing the next remote user
2. Accepting the user's commands
3. Slewing the telescope to the object and tracking the object
4. Selecting the desired filter
5. Setting up the camera and controlling the integration
6. Transmitting the image data to the remote user
7. Begin the sequence again at step 2 until the allocated time expires
8. Go on to next remote user

The above sequence is sufficient to acquire images for relatively short integrations if the telescope points accurately enough to place the desired object near the center of the field of view of the camera, the focus is correct, and the tracking is good enough. If the object isn't centered well enough and or the focus isn't correct, then additional integrations would be required to properly adjust the telescope pointing and tracking, and adjust the imaging system. These corrections could use a considerable fraction of the observing time. To make the sequence efficient, user friendly, and reliable, the complete imaging system needs to be "transparent" to the remote user - a point and click operation.

The telescope functions are no different for the “Internet Telescope” than they are for any telescope, but the performance requirements are more stringent. The telescope needs to point open loop (without feedback from the image) to a fraction of the field of view, the focus needs to be stable with temperature and accommodate any focus changes needed by different filters, and the telescope needs to track sufficiently well open loop to meet the imaging requirements.

Pointing

When a telescope is operated locally, if the object is not in the field of view or not well centered in the field of view, the operator can move the telescope using the hand paddle to center the object. The remote user may have this motion capability, but it is awkward and time consuming to perform these motions at the end of a relatively slow data transmission line. It is far more efficient if the telescope goes to coordinates and places the object near the center of the field of view.

Telescope pointing is usually characterized by specifying the RMS (Root Mean Square) value for the pointing error on the sky. An RMS pointing error of about 1/4 of the field of view of the camera will usually place the object within the central 1/2 of the field of view. This value should be considered to be the absolute minimum pointing performance as some objects will fall at the edge or outside of the field of view. An object falling outside of the field of view for a remote user should be considered to be an unacceptable error. A remotely operated telescope should probably point 2 or 3 times better or about 1/10 of the field of view to avoid this problem.

Typical Pointing Performance:
The field of view is a function of the size of the detector and the focal length of the telescope. To image a large field of view, one wants a large detector and a short focal length. Unfortunately, large CCD detectors are very expensive, and short focal length, moderate to large aperture telescopes, are also expensive. Some practical examples follow using a commercially available CCD camera with a 10 mm X 10 mm CCD chip and our 1/10 of the field of view rule:

Typical Pointing Performance Required

Aperture inches	Focal Length inches	Focal Length mm	Plate scale arc sec/mm	Field size arc min.	Pointing arc sec
14 F/11	154	3910	53	8.8	53
16 F/10	160	4000	52	8.6	53
16 F/8	128	3250	64	10.6	64
20 F/10	200	5080	41	6.8	41
20 F/8	160	4000	52	8.6	52
24 F/10	240	6100	34	5.6	34
24 F/8	192	4880	43	7.1	43
32 F/10	320	8130	25	4.2	25
32 F/8	256	6500	32	5.3	32

From the table, you can see that the recommended pointing performance is 30 to 60 arc seconds RMS (1/2 to 1 arc minute). The larger the telescope, the better the pointing performance needs to be. These values are "open loop" pointing, that is, with no optical feedback from the image.

With optical feedback, the required pointing becomes a function of the field of view for acquiring the image which may be smaller than the science imager field. There are some additional complications which are discussed later.

Initialization

Reasonably good time keeping and initialization hardware and software need to be part of the "Internet Telescope" control system to allow an auto-initialization procedure accurate enough to automatically find the first star. The time keeping should be good to one second. The initialization hardware (home sensors for example) needs to be good to about 15 arc seconds.

Focus Stability

Efficient use of the "Internet Telescope" requires that the telescope focus remains within an acceptable tolerance during the entire night's operation over temperature changes and at different zenith distances. The temperature compensation may be accomplished passively, for example, by using Invar spacers, or by an active control. If an active focus temperature compensation is used, it probably should only adjust the focus when the telescope is not integrating. Any image motion due to focus movement should be very small - a few arc seconds at most.

The focus mechanism needs to have sufficient motion resolution so that the smallest change in focus motion does not increase the image size significantly compared to the seeing disk. Also, the focus motion needs to be encoded at a resolution equal to or finer than the minimum focus motion. This is especially true when using a CCD camera, because the readout (and data transmission) may require considerable time. Time spent focusing the telescope reduces the efficiency of the system.

Each filter has an optimum focus position. It is advantageous to have a focus drive system that can automatically set the telescope focus position for each filter when the filters are selected.

If the remote user is allowed to change the focus position, then there needs to be an automatic return to the nominal focus position for each new user. This will prevent the last user from leaving the telescope in an unknown focus position.

Focus Stability

(continued)

The following table shows some examples of the optical spacing change to produce a 0.2 arc second image enlargement due to defocus:

Optical Spacing Change for 0.2 Arc Second Defocus

Telescope Size		Allowable Spacing Change of Optics	Allowable Temperature Change of Aluminum Structure
Aperture	Design	microns	F. degrees
14-inch	F/2-F/11	1.4	0.20
16-inch	F/2-F/10	1.6	0.20
16-inch	F/3-F/8	3.2	0.32
20-inch	F/3-F/8	4.0	0.34
24-inch	F/3-F/8	4.8	0.36

The first two optical systems show a defocus effect that is very sensitive to the change in optical spacing due to the large amplification by the secondary mirror. The temperature change that produces 0.2 arc second image enlargement in an uncompensated aluminum structure is shown in the fourth column.

All of the above optical systems are very sensitive to temperature changes when fabricated from an uncompensated aluminum structure. A steel structure will be about 1/2 as sensitive. Some form of temperature compensation should be employed. A passive system using Invar spacers will be about 100 times less sensitive than the uncompensated aluminum structure. An active system will require frequent focus adjustments - perhaps as often as once every few seconds. If there is any image motion due to the focus motion, it will require a guiding system fast enough to remove the image motion. This will limit the ability of the autoguider to integrate to see faint guide stars.

Using an Invar spaced temperature compensated structure at a less than ideal site should allow the use of a F/3-F/8 telescope over a temperature range of about 50 F degrees without actively correcting the focus for temperature. It is possible to improve on the Invar spaced metering system using additional temperature compensating elements. Another approach is to use a carbon fiber reinforced composite structure. Such a structure can be made with a zero temperature coefficient at great effort and expense. Commercially available carbon fiber composite tubes are typically not as good as Invar spaced structures.

Tracking Performance

The ideal "Internet Telescope" would track for the entire imaging integration with an error too small to be seen in the image. Depending upon the site seeing, this may mean tracking to a fraction of an arc second. Even a "perfect" telescope can't track to a fraction of an arc second for more than a few seconds. The earth's atmospheric refraction at a modest zenith distance can easily change the Right Ascension tracking rate by 0.01 arc seconds per second and introduce a Declination tracking rate of 0.01 arc seconds per second. A 20 second integration will see a motion of more than 0.2 arc seconds which is noticeable. The seeing will also introduce image motions of a similar or larger amount.

Examples of the change in tracking rates due to the earth's atmospheric refraction at DEC = 0 and 35 degrees latitude:

Tracking Rates for Refraction Correction

Hour Angle	Right Ascension rate change	Declination Rate arc sec/second
-3.5 hours	-.007	-.006
-4.0 hours	-.011	-.011
-4.5 hours	-.023	-.023
-5.0 hours	-.068	-.069
-5.5 hours	-.182	-.184

From this data, you can see that without correcting the tracking rates (R.A. and DEC.) at 4.5 hours you cannot track for more than about 50 seconds with a tracking error of 1 arc second without guiding even with a perfect telescope.

The best tracking telescope we have experience with is the US Naval Observatory 1.3 meter F/2.2-F/4 telescope at Flagstaff, Arizona. This telescope will keep a star image within a 1 arc second box for more than 20 minutes open loop (no optical feedback). This telescope also has a fully temperature compensated optical tube assembly (OTA) structure so there is no optical spacing change due to temperature changes.

At less than ideal sites, a telescope that tracks very well may be satisfactory for short integrations of perhaps up to 1 minute in duration. However, in good seeing conditions, some form of autoguiding is necessary. This is one area where the technology has not been well developed for remote internet observing.

The telescope should be able to track open loop for many seconds with a tracking error of less than 1 arc second. The tracking should also be very smooth so guiding corrections need to be applied only occasionally.

Tracking Rates

The “Internet Telescope” and control system should allow the remote user to input tracking rates in R.A. and Declination of up to a few arc minutes per second. These rates would allow satellite tracking, for example. When a new remote user is granted access to the telescope, the tracking rates need to be reset to sidereal.

Guiding

Optical feedback from the “Internet Telescope” is needed to correct the telescope tracking when the integration time becomes more than a few seconds under good seeing conditions. With less than ideal conditions, a telescope that is well corrected may track open loop for tens or perhaps hundreds of seconds. Spectrographic or photometric instruments require a reduced level of tracking accuracy. Direct imaging requires tracking to a fraction of the seeing disk. In good seeing conditions this can mean guiding to 0.25 arc second or better.

Direct imaging with high precision or long integration times really needs to be guided. The challenge is finding a suitable off axis guide star and positioning the guide probe and detector on the star. Once the guide star is located, the actual mechanism to determine the centroid of the guide star's image and provide guide corrections to the telescope control system is fairly straight forward.

The classical approach is to center the target object in the field of view of the imaging camera and then offset the guide probe to the coordinates of a previously selected guide star or to move the guide probe in a search pattern until a suitable guide star is found. Often suitable guide stars are selected prior to the observing session for each field to be imaged. The offsets are calculated and the guide probe is driven to the proper offset to acquire the guide star. With prior knowledge of where to look for the guide star, this approach is fairly efficient. Without prior knowledge, searching for a suitable guide star can consume considerable observing time - especially if the guide detector has a relatively small field of view, has to integrate for many seconds, or reads out the image slowly.

Auto Guiding

An "Internet Telescope" needs to be simple to use. This implies that locating and using a guide star is totally automatic. We cannot expect the remote user to input the coordinates of the guide star with every desired field to be imaged. The selection of the guide star needs to be performed by the telescope or autoguider control system. Locating the guide star is another pointing problem. Typically, the field of view of the guide detector is considerably smaller than the main imager further increasing the need for accurate telescope pointing.

Under reasonable seeing conditions, the autoguider should be able to find a star with sufficient brightness to allow guiding with less than a few seconds integration. The telescope response to the auto guider should be sufficient to allow the telescope to track to a fraction of an arc second.

DFM Engineering is developing the "Smart Autoguider"™. This system will be added to our Telescope Control System and is needed to make the "Internet Telescope" a reality.