SSOS: A Moving-Object Image Search Tool for Asteroid Precovery

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Received 2011 November 24; accepted 2012 April 18; published 2012 May 18

ABSTRACT. It is very difficult to find archival images of solar system objects. While regular archive searches can find images at a fixed location, they cannot find images of moving targets. Archival images have become increasingly useful to extragalactic and stellar astronomers the last few years, but until now, solar system researchers have been at a disadvantage in this respect. The Solar System Object Search (SSOS) at the Canadian Astronomy Data Centre allows users to search for images of moving objects. SSOS accepts as input either a list of observations, an object designation, a set of orbital elements, or a user-generated ephemeris for an object. It then searches for images containing that object over a range of dates. The user is then presented with a list of images containing that object from a variety of archives. Initially created to search the CFHT MegaCam archive, SSOS has been extended to other telescope archives, including Gemini, Subaru/SuprimeCam, HST, several ESO instruments, and the SDSS, for a total of 6.5 million images.

1. INTRODUCTION

In many fields of astronomy, image archives are of increasing importance. For example, since 2005, more than 50% of Hubble Space Telescope (HST) papers have been based on archival data, rather than on PI data.1 Archival images have become increasingly useful to extragalactic and stellar astronomers the last few years, but until now, solar system researchers have been at a disadvantage in this respect. While regular archive searches can find images at a fixed location, they cannot find images of moving targets.

This is unfortunate, because it could be argued that archival data are potentially more useful to solar system studies than to extragalactic or stellar astronomy. The full scientific potential derived from the discovery of small solar system bodies (SSSBs) cannot be fully realized until precise orbital parameters for those objects can be determined. The object must be tracked over successive nights to obtain an approximate orbit, then over the course of months and years to refine the object’s orbit. But if precovery images containing the object can be found and the object can be unambiguously identified in those images, the orbit can be rapidly refined by extending the observed arc into the past.

While a small number of dedicated SSSB surveys have been done and do include the images needed for tracking such objects, the majority of ground-based imaging surveys do not include a SSSB discovery component. Indeed, the very requirement of precise orbital determination is exactly why such surveys do not typically include SSSB discovery. For example, over 6000 deg² of sky have been imaged with the Canada-France-Hawaii Telescope (CFHT) MegaPrime camera. However, only a small fraction of these images have been carefully searched for SSSBs. These unsearched images are likely to provide a rich repository of astrometric measurements for future SSSB surveys.

The earliest example of the utility of archival data in solar system studies is the discovery of Neptune. While it is well known that the search for Neptune was prompted by perturbations in the position of Uranus, it is less well known that some of the observations of Uranus that went into these calculations were archival. Uranus had appeared (misidentified as a star) in various catalogs going back to 1690, before its discovery as a planet in 1781. Le Verrier (1846) and Adams (1846) used these critical observations in their calculations to determine the probable location of Neptune.

Of course, archival images can be useful even if the object’s orbit is well known. For example, one may want to generate a light curve for an object. Alternatively, one may want observations of an object at different wavelengths to measure an object’s color. Or, in the case of binary system, the heliocentric orbit maybe well known, but one may want additional observations to constrain the mutual orbit.

The Solar System Object Search tool (SSOS)2 at the Canadian Astronomy Data Centre allows users to search for images of moving objects taken with a number of telescopes. As input, SSOS accepts either a list of observations, an object designation, a set of orbital elements, or a user-generated ephemeris for an object. It then searches for images of that object over

1 See http://archive.stsci.edu/hst/bibliography/pubstat.html.
2 See http://www.cadc.hia.nrc.gc.ca/ssos.
a range of dates. The user is then presented with a list of images containing that object from a variety of archives.

A number of related tools and services already exist. The ESO (European Southern Observatory) archive has a service¹ that allows searches for images of known objects in HST images. The searches are precomputed. Each HST image is searched using SkyBoT (Berthier et al. 2006) for known objects. However, the tool is limited to the HST, and one cannot search for new objects.

The SkyMorph service² allows users to search for HST images, images from the Near-Earth Asteroid Tracking system (Pravdo et al. 1999), Spacewatch (Gehrels & McMillan 1982) images, and a number of older plate catalogs. Input is by object designation or by orbital elements.

The EURONEAR project (EUROpean Near-Earth Asteroids Research; Vaduvescu et al. 2009) provides a service that allows users to specify Near-Earth Asteroids by name and to search the Bucharest Plate archive and the Canada-France-Hawaii Telescope Legacy Survey³ for images.

A tool similar to SSOS has been developed by IPAC (Infrared Processing and Analysis Center; Groom 2010, private communication). The Moving Object Search Tool (MOST)⁴ has been released for use with the Wide-field Infrared Survey Explorer (WISE) telescope. As input, the tool takes an object name or a set of orbital parameters that are converted into an ephemeris of the object as seen from the spacecraft. MOST then converts that ephemeris into a series of rectangles on the sky plane for a set of orbital parameters that are converted into an ephemeris of the object as seen from the spacecraft. However, the tool is limited to the HST, and one cannot search for new objects.

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The Pan-STARRS (Panoramic Survey Telescope and Rapid Response System; Hodapp et al. 2004) project is also developing a similar tool to search for Pan-STARRS images (Jedicke 2012, private communication). It has not yet been released to the public. The tool generates the positions of all known (or synthetic) objects at the beginning, middle, and end of each night. It then fits a quadratic (in right ascension and declination) to the positions to predict the position of the objects as a function of time through the night. The tool maintains two kd trees: one for available fields and one for predicted positions. When searching for a given object, the field tree is searched; then, using the functional motion fit, it predicts the images in which the object is likely to lie. For each of the likely images, a full n-body ephemeris is done at the time of the exposure, and the object’s position is checked against the image’s coverage.

SSOS allows searches by a greater number of input methods, allowing searches for recovery images of newly discovered objects. Second, while SSOS was originally developed for searching for images taken with MegaCam on CFHT, it has been extended to include images from several other telescopes. With the exception of SkyMorph and EURONEAR, other search tools are currently limited to a single telescope.

Before SSOS can be used, a list of archival images from different telescopes is compiled, as detailed in § 2. The first step of each SSOS query is to convert the user’s input into an ephemeris using one of several methods, as described in § 3. Next, SSOS searches along that ephemeris for images as described in § 5.

### 2. Image Harvesting

Before any queries can be made, the SSOS image database must be populated. This is done by going to the various telescope archives and harvesting the metadata that describes each image taken by the telescope. For each image, the SSOS stores the following information:

1. Midpoint of exposure time.
2. Right ascension and declination of the image center.
3. The extent of the image in right ascension and declination.

Some images are not rectangles and some are not square to the right ascension and declination gridlines. In this case, SSOS stores the extrema of the images in both coordinates.

For some archives (e.g., HST and most of the MegaCam archive), the position of the images is known to within an arc-second or two. For other archives, the image positions are less well known. To ensure that no image is missed due to a faulty position in a search, the image extent is increased slightly to compensate; a buffer is added in both right ascension and declination. The size of the buffer depends on the typical astrometric quality of an archive. A further buffer of 15′′ is added in both directions to allow for any ephemeris errors.

These buffers increase the completeness, but slightly decrease the purity of the searches. When searching for a given object, the search results are unlikely to miss any images containing the object, but may contain a few false positives. In practice, removing all the false positives is impossible. For instance, many of the instruments in the database are mosaic cameras (e.g., MegaCam, SuprimeCam, and VISTA), which have gaps between the detectors. False positives will occur if an asteroid happens to lie in a gap during the exposure.

These parameters (time, center, and extent) are the minimum required to find the image. When the world coordinate system of an image is available and accurate, this is also stored in order to refine the search, as detailed in § 4.2.

To speed the searches, a bounding box is generated for each image. The bounding box completely encloses the image and is described in integer degrees. Again, to speed the search, the exposure midpoint expressed as a MJD is truncated and stored as an integer.

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¹ See http://archive.eso.org/archive/hst/solarbodies/.
² See http://skyview.gsfc.nasa.gov/cgi-bin/SkyMorph/mobs.pl.
³ See http://euronear.imcce.fr/tiki-index.php?page=Precovery.
⁴ See http://irsa.ipac.caltech.edu/applications/wise/#id=Hydra_wis_wise_5.
⁵ See http://archive.eso.org/archive/hst/solarbodies/.
⁶ See http://archive.eso.org/archive/hst/solarbodies/.
⁷ See http://archive.eso.org/archive/hst/solarbodies/.
Images that span the celestial meridian have two entries in the database: one entry describing the part of the image lying above $R.A. = 0^\circ$ and the other describing the part of the image lying below $R.A. = 360^\circ$. No special provision is made for images covering the poles, since there are none in the database.

SSOS stores some additional parameters describing each image:

1. Exposure time.
2. Filter.
3. Telescope/instrument.
4. The URL at which the data can be retrieved.

The first three of these give some indication of whether the data will be useful. For example, some users may not want data in a certain filter, others may only be looking for high-resolution data, and short-exposure images might be too shallow for some objects. The URL will allow the user to actually retrieve the data once found.

Obtaining the metadata for images stored at the Canadian Astronomy Data Centre (CADC), where SSOS is based, is relatively easy. The existing databases that describe each image archive are queried directly, and the relevant parameters are ingested into the SSOS database. In some cases, the headers of the individual FITS images are retrieved to obtain additional metadata. Currently, the following telescopes and instruments have been harvested from the CADC:

1. CFHT: MegaCam, WIRCam, and CFH12K.
2. Gemini: GMOS images only.
3. *HST*: WFPC (Wide Field Planetary Camera), ACS (Advanced Camera for Surveys), and WFC3 (Wide Field Camera 3)

Off-site archives must be “scraped” over the World Wide Web. This can take many forms, depending on the archive. The Subaru SuprimeCam image lists are available as simple ASCII text files. The ESO archive can be queried by instrument; while such a query takes many hours, it will return a list of every image made by that instrument. Currently, the following telescopes and instruments have been harvested from the CADC:

1. AAT (Anglo-Australian Telescope): WFI (Wide-Field Imager).
2. ESO-LaSilla 2.2 m: WFI.
3. ESO-NTT (New Technology Telescope): ESO Faint Object Spectrograph and Camera), EMMI (ESO Multi-Mode Instrument), SOFI (Son of Isaac), and SUSI1 and SUSI2 (Superb Seeing Imagers).
4. ESO-VISTA (Visible and Infrared Survey Telescope for Astronomy): VIRCAM (VISTA IR Camera).
5. VLT (Very Large Telescope): FORS1 and FORS2 (Focal Reducer/low-dispersion Spectrograph), HAWK-I (High Acuity Wide field $K$-band Imager), NAOS-CONICA (Nasmyth Adaptive Optics System—Coudé Near-Infrared Camera ISAAC [Infrared Spectrometer and Array Camera]), and VIMOS (Visible Multiobject Spectrograph) imaging.

Images from the NOAO archive, VST (OmegaCam), and the Isaac Newton Group of telescopes will be added in the future.

In principle, data from any instrument can be ingested into SSOS. So far, ingestion efforts have concentrated on image archives from telescopes with larger apertures or larger fields of view. Only data taken in broadband filters are included; narrowband data tend to be too shallow for to be useful for precov- er. Finally, only images taken in optical or near-infrared bands have been harvested to date.

Currently, there are 1.6 million images in the SSOS database. Figure 1 shows the area of the sky covered by SSOS. The figure indicates the number of images by grayscale. The darkest patches are covered by at least 40 images. The figure does not indicate the depth or wavelength of the images. Although substantial fraction of the southern hemisphere has been cov- ered repeatedly by the VIRCAM detector, the exposure time of these infrared images is typically less than a minute. As dis- cussed in § 6, this coverage is sufficient when two-thirds of the asteroids in the MPC (Minor Planet Center) database lie within at least one image and a typical asteroid is covered by 20 images.

3. USER INPUT AND CONVERSION TO EPHEMERIS

When arriving at the Solar System Object Search tool Web site, users have four ways to search for images. In each case, SSOS converts the user’s input into an ephemeris. The four methods of input and conversion are detailed in the following four subsections.

3.1. Search by Arc

In this input method, the user enters a series of observations in MPC format. SSOS uses these observations to determine an orbit and generate an ephemeris from that orbit. The user can select one of two orbit-fitting routines: The orbit-fitting code of Bernstein & Khushalani (2000) has been set up to automatically convert the observations into orbital parameters (the fit code) and to use those parameters to produce an ephemeris (the predict code). The Bernstein and Khushalani code works best for outer solar system objects; if the arc of a main- belt asteroid is too short, it tends to produce spurious results. Therefore, SSOS provides the new object ephemeris generator from the Minor Planet Center as an alternative. If a user selects

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7 See, e.g., http://smoka.nao.ac.jp/status/obslog/SUP_2009.txt.

8 See http://www.minorplanetcenter.net/iau/info/OpticalObs.html.

9 See http://minorplanetcenter.net/iau/MPEph/NewObjEphems.html.
this option, the SSOS queries the MPC service automatically. The MPC fits a Väisälä (Väisälä 1939) orbit to the observations and returns an ephemeris based on this orbit. SSOS then uses that ephemeris. This method is slower than the Bernstein & Khushalani (2000) fitting, because it requires SSOS to make a query (often several queries) to an external service. The ephemeris is generated at intervals of 24 hr. Mauna Kea (observatory code 568) is used as the observing site.

3.2. Search by Object Name

In this input method, the user enters the name of an object. SSOS forwards that name to one of two services: either the Lowell Observatory asteroid ephemeris generator\(^\text{10}\) or the minor planet and comet ephemeris service at the Minor Planet Center.\(^\text{11}\) These services query their databases for an object matching the name, make the appropriate orbital calculations, and return an ephemeris to SSOS. SSOS parses the ephemeris from the external services into a format that it can use for the image search.

In addition to using these two off-site services, SSOS can also generate an ephemeris locally. SSOS maintains regularly updated copy of the MPC orbital element database.\(^\text{12}\) When a user enters an object name, the local version of this database is queried and the orbital elements are passed to the program \texttt{orbfit} of Milani & Gronchi (2010),\(^\text{13}\) which generates an ephemeris.

As with the search-by-arc option, the ephemeris is generated at 24 hr intervals, and Mauna Kea is used as observing site.

3.3. Search by Orbital Elements

In this case the user enters the orbital elements of an object: epoch, semimajor axis, eccentricity, inclination, longitude of the ascending node, argument of perihelion and mean anomaly. These orbital elements are used as input to the program \texttt{orbfit}, which returns an ephemeris, again at 24 hr intervals and using Mauna Kea as the observing location.

3.4. Search by Ephemeris

This method allows the user complete control over the ephemeris. The user enters a series of times and object positions. Users can cut and paste text into the service. This method is useful if the user has any concerns about the positional accuracy of any of the previous methods. This might be because the object being searched for is near enough to the Earth that the parallax will significantly affect the object’s positions. Alternatively, the object’s apparent motion might be irregular enough that the linear daily interpolation scheme is insufficiently accurate. Finally, the user might have concerns about the accuracy of the program generating the ephemeris.

3.5. Ephemeris Accuracy

For the first three types of searches, the ephemeris is generated with Mauna Kea as the reference location, because two of the most useful instruments in the SSOS database are located there. In this sort of search, usefulness can be quantified as mirror area times field of view times years in operation. MegaCam on CFHT and SuprimeCam on Subaru are the clear leaders. Mauna Kea is also the location of Gemini North. However, the rest of the telescopes are at other locations on the Earth, while \textit{HST} is in orbit. How much does the assumption of Mauna Kea as the observing location affect the ephemeris?

For main-belt asteroids, the assumption will introduce errors of ~10'' at most. The parallax error is on the order of 1 Earth radius divided by 1 AU (approximately the closest approach of a main-belt asteroid), which is 8''. For more distant objects, such as Kuiper Belt objects (KBOs), the error will be significantly less. In the extreme case of near-Earth objects, the parallax error can be much greater, but for short periods. In the vast majority of cases, the 15'' buffer described in § 2 is sufficient.

Again, for the first three types of searches, the ephemeris is generated at 24 hr intervals. For times between these points, linear interpolation is used to determine the location of the object, as detailed in the following section. This is done for reasons of speed. But how much is the ephemeris accuracy affected relative to, for example, an hourly ephemeris?

This was tested by generating ephemerides at 15 minute intervals for a few key objects: a KBO, a main-belt asteroid, and an Apollo: Pluto (134340), Ceres (1), and Eger (3103). The positions were compared with the results of the linear interpolation described in § 5. The size of the resulting offsets were smaller than the parallax errors above: less than an arcsecond for KBOs, a few arcseconds for main-belt asteroids, and, while generally small for the Apollo asteroids, occasionally as large as 2–3''.
Again, the buffers added to the image extents described in § 2 should be sufficient in most cases.

In exceptional cases, users will have to use the direct ephemeris input method described in § 3.4. Alternatively, if an increased false-positive rate is acceptable, they can increase the positional uncertainty, as described in the following section.

4. ADDITIONAL INPUTS

4.1. Positional Uncertainty

In addition to ephemeris information, the user can also specify positional uncertainty information. This is useful if an object’s ephemeris is not perfectly known. Instead of searching only for images containing the object’s assumed location, the search is broadened to include images nearby. The search is increased from a point to a search box whose size is specified by the user. In most cases, the size of the search box is fixed. However, if an arc search using the Bernstein & Khushalani (2000) code is selected, then the user can choose to use the error ellipse generated by the code. The search box at each location grows to contain the error ellipse.

4.2. Positional Resolution

The MegaPrime mosaic camera on CFHT consists of 36 separate CCDs. Each MegaCam image is large: 700 Mbytes (300 Mbytes in compressed format). Downloading a large number of the these images can be time-consuming, depending on the user’s bandwidth. However, the images are stored in multi-extension FITS format. It is possible to download a single extension (corresponding to a separate chip) from the CADC. At about 16 Mbytes in size, it offers an attractive alternative to the full image. Therefore, SSOS offers an option to resolve the search down the extension level for MegaCam images. This option is only available for the MegaCam images that have been calibrated using the MegaPipe pipeline: currently, about 75% of the total MegaCam archive. When this option is active, the search returns a link to the image extensions that likely contain the object being searched for. If the positional uncertainty is specified (as in § 4.1), links to all the CCDs spanned by the error box are returned.

Similarly, SSOS also has the option to resolve down to the pixel coordinates within a single chip. The stored world coordinate system for that chip is used to convert the right ascension and declination of the object to an XY pixel location that is returned to the user.

5. SEARCHING ALONG THE EPHEMERIS

Once the first step of generating an ephemeris has been accomplished, the next step is to match that ephemeris to the database of images. The ephemeris is converted to a temporary database table. Each interval in the ephemeris becomes a row in the table, with start and end times and positions. A bounding box is generated for each row, covering the full span in time and position. For speed, this bounding box is expressed as integer days (for the time) and integer degrees (for position). When the object moves across the first point of Aries, two rows are added: one each describing the position of the object on either side of the celestial meridian. If the time interval spans multiple days (for example, if the user-generated ephemeris has been produced at weekly intervals), additional rows, one per day, are added to this table. This temporary table is comparatively small. If the ephemeris is sampled daily, just under 8000 rows suffice to cover the time span from the earliest image in the SSOS database to the present. Building the temporary table takes 2–3 s for a full 20 yr span.

The ephemeris table is then cross-matched to the image table; in the terminology of relational databases, they are “joined.” The integer bounding boxes of the ephemeris and the images are matched first. If the bounding boxes of an ephemeris and an image match, the object’s position is calculated more accurately at the image’s exposure midpoint by linearly interpolating the ephemeris. The linear interpolation is key to keeping the queries reasonably fast. Doing a full orbital prediction for each of the images is not feasible. This is sufficiently accurate for the majority of queries, where the object either moves slowly or in a fairly straight line. For faster-moving nearby objects, it may be necessary to supply the ephemeris sampled at shorter time steps, as discussed in § 3.5. If a spline method is used (rather than linear interpolation), the positional accuracy increases, but only by a few percent and at considerable computational cost. A typical cross-match takes 0.3 s to match a 20 yr ephemeris to 1.6 million images.

6. RESULTS AND PERFORMANCE

The results page presents the user with a table listing the image name, exposure midpoint, filter name, exposure time, object’s position at exposure midpoint, image target name, and links to more metadata. If possible (for example, if the image is hosted at the CADC), SSOS provides a direct HTML link to the image. For data centers such as the Subaru archive and ESO, which operate on the request-stage-retrieve model, SSOS provides a link to the request Web page for that image.

In addition to providing a table, SSOS provides a plot showing the location of the object on the sky, with a line showing the object’s location and dots showing matching images. This information is also made available as a ds9 regions file.

The speed of the search depends on which ephemeris method is used and the time span being searched. The fastest example is if the orbit-fitting method of the Bernstein-Khushalani method is used and the time span is short: a few months before and after the input observations. This would make the span useful for recovery of a newly discovered object. In this case, the search would require less than a second to generate the ephemeris, build the temporary table, and match to the SSOS image table.
On the other hand, if one searches by object name, sets the span to the full 20 yr span of the SSOS image database, and requests that the MPC be used to generate the ephemeris, the search will take longer. The MPC queries can take \( \geq 10 \) s (depending on the load on the MPC servers), it will take 2–3 s to generate the temporary ephemeris table, and the cross-matching will take a second. The represents the slowest possible search.

How likely is it that SSOS will find images of a particular object? And how many images of an object is it likely to find? Obviously, if a typical search does not return any images, the service is not very useful. This was investigated by searching for images of 566,253 objects from the MPC orbital element database. It was found that of these searches, 384,786 returned at least one image; i.e., just over two-thirds of the searches were successful. The results are shown in Figure 2. The number of images returned by the searches is shown as a histogram. Searches returning no images are shown as a separate histogram bar. In some cases, several hundred images are returned. If only the successful searches (i.e., the searches returning at least one image) are considered, the average number of image returned is 30. The average number of images returned over all searches is 20 (including the one-third of the searches that returned nothing).

Note that this is just the number of images returned, which may not be a good indication of how many useful observations may be derived from these images. SSOS will only find the images containing an object. It does not generally find the position of that object in the images. Where the orbital parameters are poorly known, positional uncertainty may make it difficult to find the object in question. Indeed, if the position is poorly known and the image’s field of view is small, all that SSOS can report is that the image probably contains the object. If there are many moving objects in the images, it may be difficult to unambiguously identify the object in question. Unless there are multiple images of the object close together in time, it will be difficult or impossible to identify the object. Alternatively, there may be enough images coincident in position and time, but taken in different wavelengths, making it more difficult to identify the moving object. As noted in § 2, some of the instruments described in SSOS are mosaic cameras with gaps between the detectors; SSOS does not describe the footprint of the cameras in detail, so objects may fall between the gaps. Finally, there is no guarantee that the images returned are deep enough to detect the object, even if it covers the correct patch of sky.

7. USAGE

To date, SSOS has been used successfully in a number of projects. Parker et al. (2011) used the tool to locate additional data of wide-binary trans-Neptunian objects. SSOS found images in the HST and Gemini archives that were used to constrain the mutual orbit of the binaries.

The SSOS tool was used by the Canada-France Ecliptic Plane Survey (CFEPS; Petit et al. 2011) project in two ways. First, they used the tool to retrieve the survey’s images of particular KBOs. This allowed the rapid reanalysis of the discovery data to search for binaries among the CFEPS KBOs (Lin et al. 2010). Second, the ability to easily return to the search data allows members external to the original survey to enhance the survey data set. The search tool was also used to look for, and find, pre- and postdiscovery images of the KBOs discovered by the CFEPS project.

SSOS is also part of the KBO search in the Next Generation Virgo Survey (NGVS; Ferrarese et al. 2012, in preparation). While the main purpose of the NGVS is the study of the properties of galaxies in the Virgo cluster, the same data are being used to search for KBOs. SSOS is used to search for additional images of the newly detected KBOs.

Alexandersen et al. (2012, in preparation) discovered a Jovian moon in 2010. Using SSOS and its user-generated ephemeris feature, they were able to find precovery images dating back to 2003 from the CFHT MegaCam archive.

Finally, Fraser et al. (2012, in preparation) used SSOS for precovery of Kuiper Belt objects as part of a follow-up program of objects discovered in Fraser et al. (2010). These targets are part of a large sample used to determine the size distribution of different Kuiper Belt dynamical populations, which will help constrain the formation history of the outer solar system.

FIG. 2.—Number of images containing an asteroid. The figure was generated by feeding all the objects in the MPC orbital element database into SSOS and plotting the number of returned images as a histogram. Note that the axis is logarithmic. Searches returning no images are shown as a separate histogram bar. Two-thirds of the searches return at least one image. On average, an image search for given object will return 10 images, but with considerable scatter.
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