WCSTools 3.0

Tools for Image Astrometry and Catalog Searching

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Astronomical Catalogs Supported by WCSTools

Catalog or Format	No. Stars	Bytes	Region Search	Image Search
USNO-A2.0 Catalog	526,280,881	6,315,370,572	sua2 (scat)	imua2 (imcat)
GSC II Catalog	455,851,237	?	sgsc2 (scat)	imgsc2 (imcat)
2MASS Point Source Catalog	155,569,249	48,988,432,908	stmc (scat)	imtmc (imcat)
USNO-SA2.0 Catalog	55,368,239	664,418,868	susa2 (scat),	imusa2 (imcat)
GSC-ACT Catalog	25,541,952	1,231,787,520	sgsca (scat)	imgsca (imcat)
HST Guide Star Catalog	25,541,952	1,231,787,520	sgsc (scat)	imgsc (imcat)
Tycho-2 Catalog	2,539,913	528,721,576	sty2 (scat)	imty2 (imcat)
USNO/Hipparcos ACT Catalog	988,758	318,380,076	sact (scat)	imact (imcat)
PPM Catalog	378,910	22,734,656	sppm (scat)	imppm (imcat)
SAO Catalog	258,996	15,539,876	ssao (scat)	imsao (imcat)
IRAS Point Source Catalog	245,889	7,376,698	siras (scat)	imiras (imcat)
Hipparcos Catalog	118218	4492312	ship (scat)	imhip (imcat)
Starbase tab-delimited ASCII	varies	varies	scat	imcat
Space-Delimited ASCII	varies	varies	scat	imcat
Local Binary	varies	varies	scat	imcat
USNO-A1.0 Catalog	488,006,860	5,856,082,320	sua1 (scat)	imua1 (imcat)
USNO-SA1.0 Catalog	54,787,624	657,451,488	susa1 (scat)	imusa1 (imcat)
USNO J-1.0 Catalog	19,911,514	238,938,168	sujc (scat)	imujc (imcat)

The GSC II Catalog over the World Wide Web

All WCSTools programs which access the GSC II Catalog the web. Code to assemble and send http queries to the STScI GSC II server is built into the GSC II access subroutine. Since tab-separated Starbase tables, a native WCSTools catalog format, are an output option from the catalog server, they are parsed and sorted just like local Starbase files.

The following example searches a 3 arcminute radius circle around 10:00 30:00 J2000 and returns all of the stars found there, sorted by their distance from the search center. The verbose mode (-v) echoes the http query sent.

```
$ sgsc2 -s p -vhr 180 10:00 30:00 J2000

sgsc2 3.0.5, 21 September 2001, Doug Mink SAO
Center:  10:00:00.000   +30:00:00.00 J2000
Area:    00:00:27.71 x +00:06:00.00
     gsc2  10:00:00.000 +30:00:00.00 J2000 r= 180.00 at epoch 2000.00

http://www-gsss.stsci.edu/cgi-bin/gsc22query.exe?ra=10:00:00.000&
dec=+30:00:00.00&r1=0&r2=3.000&m1=0.00&m2=99.9&n=100000&submit2=Submit+Request

SearchLim: RA: 09:59:46.144 - 10:00:13.856  Dec: +29:57:00.00 - +30:03:00.00
TABREAD: Catalog http://www-gsss.stsci.edu/cgi-bin/gsc22query.exe : 9 / 10 / 9 found
9 GSC 2.2
GSC II number  RA2000       Dec2000      MagF  MagJ  MagV  MagN  Arcsec
N23300138138  09:59:57.812 +29:59:41.61 99.90 19.02 99.90 99.90   33.86
N23300138176  09:59:57.363 +29:59:59.00 18.20 99.90 99.90 99.90   34.28
N23300138024  10:00:04.044 +29:58:52.62 18.22 99.90 99.90 99.90   85.44
N23300137981  10:00:00.825 +29:58:29.54 16.30 17.77 99.90 99.90   91.10
N23300138201  09:59:52.870 +30:00:11.59 18.09 19.22 99.90 99.90   93.34
N2330013430   10:00:07.759 +30:00:05.08 12.24 13.66 99.90 99.90  100.91
N23300137937  10:00:00.781 +29:58:11.02 17.41 18.69 99.90 99.90  109.45
N23300137866  10:00:07.818 +29:57:42.80 18.20 99.90 99.90 99.90  170.71
N23300137785  10:00:03.922 +29:57:11.59 17.77 19.30 99.90 99.90  175.95
```

Running the same search with a vvv flag prints the actual returned information, (the returned lines are split here to fit on the page):

```
$ sgsc2 -vvvhr 180 10:00 30:00 J2000

sgsc2 3.0.5, 21 September 2001, Doug Mink SAO
     gsc2  10:00:00.000 +30:00:00.00 J2000 r= 180.00 at epoch 2000.00
GSC2ID          Ra            Dec           RaErr         DecErr       Epoch          RaPM          DecPM         RaPMErr
--------------  ----------    ----------    ----------    ----------   ----------     ----------    ----------    ----------
N23300138201    149.97029271  30.00321937   0.253854      0.252980     1989.927246    0.00000000    0.00000000    0.00000000
N23300137937    150.00325622  29.96972872   0.253854      0.252980     1989.927246    0.00000000    0.00000000    0.00000000
N23300138024    150.01684990  29.98128360   0.253854      0.252980     1989.927246    0.00000000    0.00000000    0.00000000
N123300138138   149.99088204  29.99489136   0.337576      0.302556     1993.195190    0.00000000    0.00000000    0.00000000
N23300137981    150.00343836  29.97487112   0.253854      0.252980     1989.927246    0.00000000    0.00000000    0.00000000
N23300138176    149.98901042  29.99972114   0.253854      0.252980     1989.927246    0.00000000    0.00000000    0.00000000
N2330013430     150.03232758  30.00141232   0.253854      0.252980     1989.927246    0.00000000    0.00000000    0.00000000
N23300137866    150.03257446  29.96188828   0.253854      0.252980     1989.927246    0.00000000    0.00000000    0.00000000
N23300137785    150.01634188  29.95321941   0.253854      0.252980     1989.927246    0.00000000    0.00000000    0.00000000

     Fmag   FmagErr Jmag   JmagErr Vmag   VmagErr Nmag   NmagErr a      e      PA     c    Status
     -----  -----   -----  -----   -----  -----   -----  -----   -----  ------ ------ ---  ------
     18.09  0.42    19.22  0.43    99.90  99.90   99.90  99.00   2.24   0.04   45.00  0    1022202
     17.41  0.42    18.69  0.42    99.90  99.90   99.90  99.00   3.37   0.28   154.37 0    1022202
     18.22  0.43    99.90  99.90   99.90  99.90   99.90  99.00   3.37   0.36   124.14 3    20202
     99.90  99.90   19.02  0.42    99.90  99.90   99.90  99.00   3.21   0.17   85.81  0    1002202
     16.30  0.41    17.77  0.42    99.90  99.90   99.90  99.00   3.15   0.04   82.67  0    1011202
     18.20  0.42    99.90  99.90   99.90  99.90   99.90  99.00   2.88   0.23   84.43  3    20202
     12.24  0.41    13.66  0.42    99.90  99.90   99.90  99.00   6.15   0.02   15.59  0    1011202
     18.20  0.42    99.90  99.90   99.90  99.90   99.90  99.00   2.86   0.23   125.38 0    1020202
     17.77  0.42    19.30  0.43    99.90  99.90   99.90  99.00   2.65   0.12   145.95 0    1022202
[EOD]
```

SCAT used over the World Wide Web

scat can call itself over the web. Code to turn http query input into the same parameters which are set on the command line is built into the main **scat** program. Code to assemble and send http queries to remote programs, such as the ESO USNO-A2.0 and GSC servers and the STScI GSC II server, as well as remote **scat** servers, is built into the individual catalog access subroutines. Since tab-separated Starbase tables, a native WCSTools catalog format, are an output option on most catalog servers, they are parsed and sorted just like local Starbase files.

```
$ setenv TMC_PATH http://tdc-www.harvard.edu/cgi-bin/scat
$ stmc -vhr 180 10:00 30:00 J2000

stmc 3.0.5, 21 September 2001, Doug Mink SAO
Center:  10:00:00.000   +30:00:00.00 J2000
Area:    00:00:27.71 x +00:06:00.00
      tmc  10:00:00.000 +30:00:00.00 J2000 r= 180.00 at epoch 2000.00
http://tdc-www.harvard.edu/cgi-bin/scat?catalog=tmcsc&ra=150.0000000&
dec=30.0000000&system=J2000&radius=180.000&epoch=2000.00000
SearchLim: RA: 09:59:46.144 - 10:00:13.856  Dec: +29:57:00.00 - +30:03:00.00
TABREAD: Catalog http://tdc-www.harvard.edu/cgi-bin/scat : 6 / 7 / 6 found
6 2MASS Point Sources
2MASS num.  RA2000       Dec2000      MagJ    MagH    MagK    Arcsec
18.1317411 10:00:07.749 +30:00:04.86 11.166  10.701  10.615   100.78
18.1316998 10:00:00.830 +29:58:29.39 15.066  14.541  14.373    91.25
18.1316910 10:00:00.845 +29:58:11.65 15.945  15.169  15.017   108.90
18.1317243 10:00:13.174 +29:59:29.74 16.281  15.585   0.000   173.80
18.1316642 10:00:03.900 +29:57:11.46 16.440  15.863  15.735   175.99
18.1317101 10:00:04.015 +29:58:52.65 16.888  15.771  15.377    85.19
```

Running the same search with a vvv flag prints the actual returned information:

```
$ stmc -vvvhr 180 10:00 30:00 J2000

stmc 3.0.5, 21 September 2001, Doug Mink SAO
      tmc  10:00:00.000 +30:00:00.00 J2000 r= 180.00 at epoch 2000.00
catalog 2MASS PSC
ra      10:00:00.000
dec     +30:00:00.00
equinox 2000.0
epoch   2000.0
radsec  180.00
catsort mag
program scat 3.0.5, 21 September 2001, Doug Mink SAO
2mass_id        ra              dec             magj    magh    magk    arcsec
----------      ------------    ------------    ------- ------- ------- ------
18.1317411      10:00:07.749    +30:00:04.86    11.166  10.701  10.615  100.78
18.1316998      10:00:00.830    +29:58:29.39    15.066  14.541  14.373  91.25
18.1316910      10:00:00.845    +29:58:11.65    15.945  15.169  15.017  108.90
18.1317243      10:00:13.174    +29:59:29.74    16.281  15.585  15.734L 173.79
18.1316642      10:00:03.900    +29:57:11.46    16.440  15.863  15.735  175.99
18.1317101      10:00:04.015    +29:58:52.65    16.888  15.771  15.377  85.18
```

WCSTools Documentation:
http://tdc-www.harvard.edu/software/wcstools/
This poster in HTML:
http://tdc-www.harvard.edu/software/wcstools/publications/adass2001
This poster in Postscript:
http://tdc-www.harvard.edu/software/wcstools/publications/adass2001/poster.ps

An Evolving Software Package

For five years, WCSTools as provided image astrometry for astronomers who need accurate positions for objects they wish to observe. Other functions have been added and improved since the package was first released.

➤ **imwcs has been improved in several ways:**
- ➣ **Fits may be repeated, with and without tightening the tolerance on matches between image and catalog stars.**
- ➣ **Any of several magnitudes in a reference catalog can be used to order the brightest stars for matching.**
- ➣ **A WCS can be fit to an initial set of X-Y/RA-Dec matches, with optional full match and fit of additional image stars.**

➤**WCSTools includes and uses Mark Calabretta's latest release of WCS-LIB,version 2.7, for projections, and supports multiple world coordinate systems in a single header.**

➤**Catalogs are now searchable over the World Wide Web. The catalog searching routine can be located on either end (or both ends!) of such a web connection, and the output from one catalog search can be used as the input to another search.**

➤**Support has been added for new catalogs, such as the GSC-ACT and 2MASS Point Source Catalog, as they have come out. Access over the web to the GSC II Catalog Server at the Space Telescope Science Institute is supported as a default. A simple command line interface can search any supported catalog, returning information in several standard formats.**

➤**scat has been made to work more like a filter, so the output of a search of one catalog can be used as input for a search of another catalog. It has also been extended so it can be used as part of a web site which serves archived spectra.**

The goal of this project is to have a good set of command line tools for dealing with images, their headers, source catalogs, and relationships between them. The FITS WCS standard will be completely supported when it is agreed upon, and access to more catalog-serving web sites will be added in the future.

Multiple World Coordinate Systems

WCSTools implements the use of multiple world coordinate systems, with the WCS to which a keyword applies designated by a suffixed upper-case alphabetic character.

Thus `CTYPE1` applies to the default WCS, which may be named using `WCSNAME`. A second WCS could use keywords such as `CTYPE1A` and `WCSNAMEA`. Up to 27 (no suffix, A-Z) different sets of WCS keywords may be specified.

In the WCSTools programs, the WCS to be used is specified by adding *`%WCSNAME`* to the end of a filename specified on the command line. This is added after the extension of a multi-extension FITS image is specified:

`fitsfile,extension_name_or_number%WCS_name_or_letter`

imwcs always sets the default (no suffix) keywords.

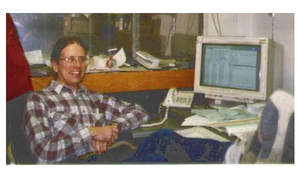
Sometimes getting from image pixels to world coordinates is best thought of as a two step process, pixel<->focal plane<->sky, for example. The keyword `WCSDEPx`, indicating a named WCS conversion which must be applied to pixel coordinates before WCS conversion x can be applied, could be added to indicate the name or letter of the requisite WCS.

Example of Multiple WCS in a FITS Header

Thanks to Steve Allen, Lick Observatory

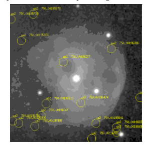
```
CRVAL1  =                  0.5
CRVAL2  =                 89.5
CRPIX1  =                    1
CRPIX2  =                    1
CDELT1  =                    1
CDELT2  =                   -1
CTYPE1  = 'TLON-CAR'           / Terrestrial East Longitude
CTYPE2  = 'TLAT-CAR'           / Terrestrial North Latitude
CUNIT1  = 'deg     '
CUNIT2  = 'deg     '
WCSNAMEI= 'image   '           / redundant reiteration of default FITS
CRPIX1I =                   1. / reference pixel along FITS axis i
CRPIX2I =                   1. / reference pixel along FITS axis i
CRVAL1I =                   1. / WCS value along axis j at refpix
CRVAL2I =                   1. / WCS value along axis j at refpix
CD1_1I  =                   1. / CTM j_i from pixel to WCS
CD1_2I  =                   0. / CTM j_i from pixel to WCS
CD2_1I  =                   0. / CTM j_i from pixel to WCS
CD2_2I  =                   1. / CTM j_i from pixel to WCS
CTYPE1I = 'IMGX-CAR'           / coordinate/projection type of axis j
CTYPE2I = 'IMGY-CAR'           / coordinate/projection type of axis j
CUNIT1I = 'pixel   '           / physical unit along WCS axis j
CUNIT2I = 'pixel   '           / physical unit along WCS axis j
```

Telescope
SMITHSONIAN ASTROPHYSICAL OBSERVATORY
Data Center



IMWCS Using Prematched stars and the USNO-A2.0 Catalog

If an image has features which make it hard to match specific stars, it is useful to match up a few image stars (5 is a reasonable number) to catalogued positions by hand. **imwcs**, as of version 2.8.7, accepts a file of x,y,RA,Dec matched positions and fits an initial world coordinate system to them. That WCS may be either written to the image header or used as an initial guess to fit a more complete list of images star positions and a deep catalog, such as the US Naval Observatory A2.0 Catalog, to get a better WCS.



This FITS image, courtesy of Andy Szentgyorgyi of the Harvard-Smithsonian Center for Astrophysics, contains the planetary nebula NGC 246, the coordinates of whose features we want to find. The header keywords

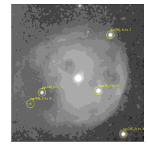
```
NAXIS   =                    2 / Number of axes
NAXIS1  =                  495 / Axis length
NAXIS2  =                  519 / Axis length
RA      = '00:44:32.90'        /MEAN RA
DEC     = '-12:08:44'          /MEAN DEC
EPOCH   = 1950.0               /MEAN EPOCH
SECPIX  =                 0.63
```

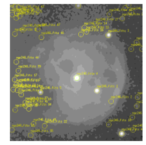
provide a nominal WCS which is used at the left by **SAOimage** and **imua2** to plot the catalog over the image.

Because the nebulosity confuses automatic star-finding programs and the reference catalogs, a prematched set of x, y, right ascension, and declination coordinates for 5 stars in the field were placed in the file *ngc246.stars*:

```
72.04   143.88  00 47 10.984    -11 53 18.92
114.91  185.80  00 47 09.153    -11 52 52.70
370.15  400.11  00 46 58.055    -11 50 36.60
325.49  191.93  00 47 00.064    -11 52 49.89
418.23   30.94  00 46 56.044    -11 54 32.13
```

These selected stars are plotted in the image at the right. These matches are used by **imwcs** to fit a WCS using header and command-line information for an initial value.



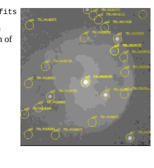


To quickly find the 100 brightest stars in the image, Emmanuel Bertin's **SExtractor** program was used through a shell script, **imse** which sets up the parameter files it needs and prepares the image, i necessary:

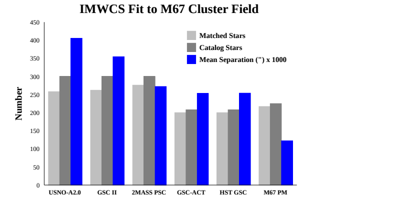
```
$ imsex ngc246.fits
ngc246.fits -> ngc246.fits
Measuring from: "NGC246_NeV" / 495 x 519 / 32 bits FLOATING POINT d
(M+D) Background: 0.0070038  RMS: 0.00744432 / Threshold: 0.0111665
Objects: detected 115      / sextracted 55
> All done
```

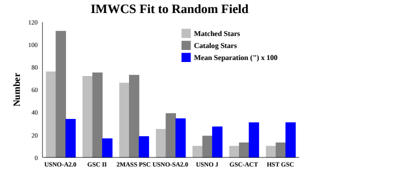
```
$ imwua2 -ew -d ngc246.sex -u ngc246.stars ngc246.fits
```

The final FITS image contains standard FITS world coordinate system keywords and a logging keyword showing what version of **imwcs** fit the WCS:



```
CRPIX1  =            247.5000      / Optical axis X coordinate
CRPIX2  =            259.5000      / Optical axis Y coordinate
WCSRFCAT= 'ua2     '               / Reference catalog
WCSIMCAT= 'NGC246_NeV_F.sex'       / Catalog of image coordinates of stars
WCSMATCH=                   9      / Number of stars matched and fit
WCSNREF =                  25      / Number of reference stars in the image
RA      = '00:47:03.422'           / Right ascension of optical axis
DEC     = '-11:52:05.70'           / Declination of optical axis
WEQUINOX=                2000      / Old Equinox
EPOCH   =                2000      / Epoch (really equinox) of WCS
RADECSYS= 'FK5     '               / Coordinate system of WCS
CTYPE1  = 'RA---TAN'               / X-axis WCS projection
CTYPE2  = 'DEC--TAN'               / Y-axis WCS projection
CRVAL1  =         11.764280414     / Right ascension of optical axis
CRVAL2  =        -11.868264512     / Declination of optical axis
CDELT1  =         -0.000176282     / Degrees of RA per pixel
CDELT2  =          0.000176973     / Degrees of Dec per pixel
CROTA1  =                0.215     / WCS rotation angle
CROTA2  =                0.215     / WCS rotation angle
WCSTOL  =              10.0000     / WCS matching tolerance in pixels
EQUINOX =                2000      / WCS equinox
SECPIX1 =               0.6346     / Arcseconds per pixel in right ascension
SECPIX2 =               0.6371     / Arcseconds per pixel in declination
WCSSEP  =                0.839     / Mean arcsec offset from catalog to image position
IMWCS   = '2.8.7, 11 January 2001, Doug Mink, SAO'
```





SCAT in the Virtual Observatory

scat can be used as a filter in a CGI script as well as running as a CGI program itself. In this case, it helps search and serve a catalog of spectra and redshifts from the Smithsonian's Z-Machine reticon spectrograph which was run on our 60-inch telescope on Mt. Hopkins in Arizona from 1978 through 1993. Output from **scat** is run through an awk script which adds the links to CGI scripts using the ID number found by **scat**. The links call a Fortran program to plot a spectrum, a C program to list information about the spectrum, and IRAF SPP programs, through CL shell scripts, to return FITS or ASCII pixel list files. The entire process is managed by a Perl script.