PEXO v2.0

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Contents

1 Introduction

PEXO is a package for making precise exoplanetology. As compared with previous models and packages, PEXO is significantly advanced and accounts for the orbital dynamics of binary motion and stellar reflex motions induced by planetary companions. PEXO treats both classic and relativistic effects such as the Roemer, Shapiro, and Einstein time delays both in the Solar System and in the target system

PEXO is able to model timing to a precision of 1 ns, astrometry to a precision of 1 microarcsecond, and radial velocity to a theoretical precision of 1 μm/s and a realistic precision of 1 cm/s. PEXO was bechmarked with the pulsar timing package TEMPO2. Theoretical and computational details of the code are described in the paper by Feng et al (2019).

2 Installation

The code is written in R and depends on several libraries. To install R on Linux, download it here or, in Ubuntu:

```
sudo apt-get install r-base
```

in MacOS:

```
brew install r
```

Clone this repository:

```
git clone https://github.com/phillippro/pexo.git
```

Install missing R libraries "cd pexo" then

```
Rscript install_dependencies.R
```

(might require su privileges to be installed): or just install them manually using install.packages('package_name') in R console.

3 Usage

3.1 Command Line

To use PEXO, one needs to go to the directory `pexo/code/` and run command lines such as

```
Rscript pexo.R -m emulate -p 'GJ551' -t '2440000 2450000 10' -i 'APF' -m 'TAR'
```

which will run a simulation of the astrometry and radial velocity variation of GJ551 from JD[UTC]=2440000 to JD[UTC]=2450000 with a time step of 10 days.

By runing

```
Rscript pexo.R -m fit -p HD10700 -N 100 -d '../input/HD10700'
```

The code will fit a single star model to the data saved in the '../input/HD10700' directory.

One can also simulate binary systems such as alpha Cen by using

```
Rscript pexo.R -m emulate -p 'HD128620' -t '2440000 2450000 10' -i 'ESO' -o '../input/HD128620.par' -C
```

One can fit a binary model to various timing, RV and astrometry data using

```
Rscript pexo.R -m fit -p 'HD128620' -N 100 -C 1 -d '../input/HD128620'
```

3.2 Input parameters

The revelant command line arguments are listed as follows.

Short name	Full name	Meaning
-m	--mode	PEXO mode: emulate or fit [optional; default=`emulate`]
-c	--component	PEXO model component: timing (`T`), astrometry (`A`), radial velocity (`R`) and their combinations [optional; default=`TAR`]
-i	--ins	Instrument or observatory [mandatory for emulation mode; default=NA]
-P	--par	Parameter file: parameters for astrometry and observatory [default: automatically obtained from simbad if not find parameter file]
-N	--Niter	Sample size of MCMC [optional; default=1000]
-C	--Companion	Companion number [optional; default=0]
-g	--geometry	geometric orbit or relativistic orbit [optional; default=TRUE]
-n	--ncore	Number of cores [optional; default=4]

Short name	Full name	Meaning
-c	--component	PEXO model component: timing (T), astrometry (A), radial velocity (R) and their combinations [optional; default=TR]
-t	--time	Two options are possible. 1. Timing file: epochs or times could be in 1-part or 2-part JD[UTC] format; 2. Format of `"Start End By"` [mandatory if mode=emulate]
-p	--primary	primary star name [mandatory]
-s	--secondary	secondary star name [default=NA]
-M	--mass	Mass of primary in unit of solar mass [optional; default=1]
-d	--data	Data directory: directory with timing, RV or astrometry data files [default= '../input/primary' where primary is the star name]
-v	--var	Output variables [optional; default=`NULL`]
-o	--out	Output file name: relative or absolute path [optional; default=`out.txt`]
-f	--figure	Output figure and verbose: FALSE or TRUE [optional; default= `TRUE`]
-V	--verbose	Verbose: FALSE or TRUE [optional; default= FALSE]

Since the astrometry and radial velocity modeling depends on the the output of timing model, `T` should always be included in the `-c` or `--component` argument.

3.3 Input timing file (only for emulate mode)

For `emulate` mode, the '-t' or '-time' argument is mendatory. It could either be a timing file or a string with `"Start End By"` format.

The timing file could be two-part or one-part JD or MJD (MJD=JD-2400000.5) in UTC time standard. The former can store epochs with precision of 10^{-14} second while the the latter can store epoch with precision of 10^{-6} second or microsecond in a 64-bit computer.

The `"Start End By"` format timing argument is composed of the start epoch (`Start`), the end epoch (`End`) and the time step (`By`). For example, a run of PEXO with `-t "2456640.5 2458462.5 0.5"` will simulate the system from JD2456640.5 to JD2458462.5 by a time step of 0.5 days. The -t argument could also be in MJD format such as `-t "56640 58462 0.5"`. The times generated from the sequence would be transformed into 2-part JD format for high precision emulation.

3.4 orbital parameter file

The orbital parameter file is specified by assigning a file path to -o or –orbit. By default, pexo will look for orbital parameters in ../input/primary.par (primary is the value of -p or –primary). A typically parameter file is as follows:

```
secondary HD128621
mass 1.1
logmC -0.09761283
logP 10.281
e 0.5179
I 79.32
omegaT 232
Omega 205
Tp 2435328.96
```

It can redefine the secondary name if `--secondary` is not given through commandline. It will give mass of the primary and the initial/optical values of logarithmic mass of companion (`logmC`), logarithmic orbital

period in days (`logP`), eccentricity (`e`), inclination (`I` in degree), argument of periastron for the primarty (`omegaT` in degree), longitude of ascending node (`Omega` in degree), and the priastron epoch (`Tp` in Julian days). In addition to these orbital parameters which is only for binaries, extra parameters of astrometry and observatory should be given for both singles and binaries. These additional parameters could either be automatically found by `PEXO` getting astrometry from Simbad (using `get_cor_from_simbad.py`) or manually given by specifying the parameter file (`-P` or `--parfile`). If specifying these parameters manually, the user should create a file with the following format. I use instrument APF/LICK and alpha Cen A for an example:

```
phi.APF 37.3425
elong.APF -121.63825
height.APF 1.274
epoch 2457206.375
ra 219.902058333333
dec -59.1660075
pmra -3679.25
pmdec 473.67
plx 743
rv -21.4
logmC -0.09761283 -10 10 U
logP 10.281 -10 20 U
e 0.5179 0 1 U
I 79.32 0 180 U
omegaT 232 0 360 U
Omega 205 0 360 U
Tp 2435328.96 2335328.96 2535328.96 U
```

The first three parameters are the latitude, longitude and height of the instrument or observatory. For fitting mode with multiple data sets, coordinates for multiple instruments are needed. The format to specify an instrument is using xxx.yyy where xxx is the coordinate name and yyy is the instrument name. Then `ra`, `dec`, `pmra`, `pmdec`, `plx`, and `rv` are the astrometric parameters from astrometric surveys such as Gaia and Hipparcos. The `epoch` parameter is the reference astrometry epoch for a given survey. The other parameteters define the priors for orbital parameters and are only necessary for fitting mode for stars with companions (i.e. –Companion>0) For example, the prior for `e` is uniform from 0 to 1. The initial values are taken from the orbital parameters given in '–orbfile' and are for initializing MCMC.

The other model related parameters are given in `../input/basic.par`. A summary definition of parameters are as follows. The bold-faced values are default ones.

parameter	unit	options or examples	meaning
RefType	-	**none**, refro, refco, refcoq	computation method for atmospheric refraction
EopType	-	**2006**, 2000B	type of Earth rotation model and corresponding Earth orientation parameters
TaiType	-	**instant**, scale	UTC to TAI method
TtType	-	**BIPM**, TAI	TAI to TT method
unit	-	**TCB**, TDB	output quantities compatible with TCB or TDB time standard
DE	-	**430**, 430t, 438, . . .	JPL ephemerides
TtTdbMethod	-	**eph**, FB01, FBgeo	TT to TDB method
SBscaling	-	**FALSE**, TRUE	linear scaling between tB and tS due to relativistic effects
PlanetShapiro	-	**TRUE**, FALSE	planetary shapiro delay
CompareT2	-	**FALSE**, TRUE	calculate uSB using TEMPO2 method for comparison

parameter	unit	options or examples	meaning
RVmethod	-	**analytical**, numerical	the method used for RV modeling, numerical is used only for comparison
LenRVmethod	-	**T2**, PEXO	the method used to derive RV lensing, T2 is used by default to be consistent with shapiro delay model in PEXO
BinaryModel	-	**none**, DDGR, kepler	binary model
ellipsoid	-	**WGS84**, GRS80, WGS72	ellipsoidal (normal) Earth Gravitational Model
epoch	JD or MJD	2448349.06250	epoch when the astrometry and position of the target is measured
observatory	-	CTIO	observatory name
xtel	metre	1814985.3	geocentric position of the telescope in the International Terrestrial Reference Frame (ITRF)
ytel	metre	-5213916.8	geocentric position of the telescope in ITRF
ztel	metre	-3187738.1	geocentric position of the telescope in ITRF
tdk	K	278	ambient temperature at the observer
pmb	millibar	1013.25	pressure at the telescope
rh	-	0.1	relative humidity at the observer (range 0-1)
wl	μm	0.5	effective wavelength of the source
tlr	K/metre	**0.0065**, any value>0	Temperature lapse rate in the troposphere
g		**1**, 0, any other values >0	one of the PPN parameters
mT	$M_\odot$	1.1055	target mass
mC	$M_\odot$	0.9373	companion mass
ra	degree	219.9175253	right ascension (RA) of the barycenter (TSB)
dec	degree	-60.8371344	declination (DEC) of the barycenter (TSB)
plx	mas	747.1700008	parallax of the barycenter (TSB)
pmra	mas/yr	-3649.4980522	proper motion in RA of the barycenter (TSB)
pmdec	mas/yr	624.7691720	proper motion in DEC of the barycenter (TSB)
rv	km/s	-22.3929553	radial velocity of the barycenter (TSB)
aT	au	10.80332	semi-major axis of the barycentric motion of the target
P	year	79.929	orbital period of the target
e	-	0.5208	eccentricity
I	degree	79.32	inclination
omegaT	degree	52.006	argument of periastron
Omega	degree	205.064	longitude of ascending node
Tp	JD or MJD	2435328.96	periastron epoch

In the above table, `epoch` is the time when the position and astrometry of the target sysstem is measured. It is `tpos` defined in the PEXO paper.

3.5 Observatory data

PEXO will first look for observatory data by finding `xtel`, `ytel`, and `ztel` from the parameter file. If it does not find these parameters, it will look for `elong` (longitude in degree), `phi` (latitude in degree) and `height` (altitude in km). If these parameters are not given, PEXO will look for the observatory name (`observatory`) and code (`ObsCode`). It will look for the observatory data in `observatories/observatory_MPC.csv` or in

observatories/satellite_list.csv. For space-based observatory, the atmospheric refraction and delay are zero and would not be implemented by PEXO. For ground-based telescope, the `RefType` parameter should be `refro` (recommended), `refco`, or `refcoq` for the calculation of refraction in astrometry modeling. If `RefType` is `none`, the atmospheric refraction is zero. The tropospheric delay and its time derivative are automatically implemented for ground-based observatories and thus do not depend on the choice of `RefType`.

For space-based observatory, "code/GetSpaceObsEph.py" will be used to find the telescope's ephemerides. So you need to install python as well as python packages `sys`, `astropy`, `numpy`, and `astroquery`.

3.6   PEXO output

3.6.1   Emulate mode

A diagram for propagation of the light ray from the target star to the observer is shown below to aid the understanding of the ouptut quantities.
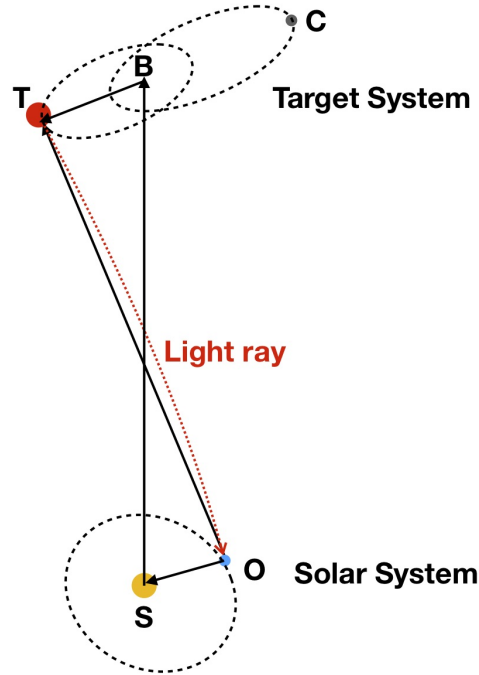

Fig. 1. Illustration of a light ray emitted from the target (T) and observed by the observer (O). The target system is composed of the target (T) and its companion (C). The binary barycenter is denoted by B. The observer is in the solar system with a barycenter at S.

There are outputs from four functions in PEXO:

`OutObs <- time_Utc2tb(utc,Par)`

`utc` is the input 2-part JD epochs, `Par` is the input and derived parametes. The output `OutObs` is a list of variables related to the transformation from JD[UTC] to JD[TCB] or JD[TDB].

```
OutTime <- time_Ta2te(OutObs,Par)
```

This function uses OutBary and Par to transform JD[TCB] to BJD[TCB] to light emission time. Thus `OutBary` and `OutTime` are the outputs from the timing models.

```
OutAstroT <- astro_FullModel(OutObs,OutTime,Par,Mlens=Par$mC,component='T')
OutAstroC <- astro_FullModel(OutObs,OutTime,Par,Mlens=Par$mT,component='C')
```

`OutAstroT` and `OutAstroC` are outputs of the astrometry modeling of the T and C component in the target system. Since the astrometry function `astro_FullModel` calls OutBary and OutTime, these astrometry outputs depend on outputs of timing model.

```
OutRv <- rv_FullModel(OutObs,OutTime,Par)
```

`OutRv` is the output of radial velocity modeling and also depends on the outputs of timing model.

These output lists will be combined as `OutAll` to be saved as ascii file if the output variables `-v` are specified in the command line.

We list the output variables in `OutAll`, their unit and meaning in the following table.

variable	unit	meaning
AbeTarget	second	target aberration delay
BJDtcb	day	BJD[TCB]
BJDtdb	day	BJD[TDB]
BT	au; au/yr	Position and velocity vectors from TSB to T
DefEarth	rad	Deflection vector due to Earth lensing
DefJupiter	rad	Deflection vector due to Jupiter lensing
DefMars	rad	Deflection vector due to Mars lensing
DefMercury	rad	Deflection vector due to Mercury lensing
DefMoon	rad	Deflection vector due to Moon lensing
DefNeptune	rad	Deflection vector due to Neptune lensing
DefSaturn	rad	Deflection vector due to Saturn lensing
DefSun	rad	Deflection vector due to Sun lensing
DefUranus	rad	Deflection vector due to Uranus lensing
DefVenus	rad	Deflection vector due to Venus lensing
delevation	rad/day	time derivative of elevation angle
delevationT2	rad/day	time derivative of elevation angle computed by TEMPO2 method
DirObs	rad	observed right ascension and declination of the target
dl.all	rad	Light deflection vector due to all effects
dl.woRef	rad	Light deflection vector due to all effects except for atmospheric refraction
dTCB.dTT	-	dTCB/dTT
dTDB.dTT	-	dTDB/dTT
dzenith	rad/day	Time derivative of zenith: dzenith/dt
EinsteinIS	second	Einstein delay due to relative motion between TSB and SSB
EinsteinTarget	second	Einstein delay in the target system
elevation	rad	elevation angle
elevationT2	rad	elevation angle calculated using TEMPO2 method
emrat	-	Earth-Moon mass ratio
Eph	-	a list of ephermerides of solar system objects
EphEarth	km; km/s	Earth ephemeris in the Barycentric celestial reference system (BCRS) frame; units are denoted by columns names
EphJupiter	km; km/s	Jupiter ephemeris in BCRS
EphMars	km; km/s	Mars ephemeris in BCRS
EphMercury	km; km/s	Mercury ephemeris in BCRS
EphMoon	km; km/s	Moon ephemeris in BCRS

variable	unit	meaning
EphNeptune	km; km/s	Neptune ephemeris in BCRS
EphSaturn	km; km/s	Saturn ephemeris in BCRS
EphSun	km; km/s	Sun ephemeris in BCRS
EphUranus	km; km/s	Uranus ephemeris in BCRS
EphVenus	km; km/s	Venus ephemeris in BCRS
GM	km; km/s	Position and velocity vector from the geocenter to the Moon
GO	km; km/s	Position and velocity vector from the geocenter to the observer/telescope
JDtai	JD	JD[TAI] or TAI
JDtcb	JD	JD[TCB] or TCB
JDtcg	JD	JD[TCG] or TCG
JDtdb	JD	JD[TDB] or TDB
JDtt	JD	JD[TT] or TT
JDut1	JD	JD[UT1] or UT1
leap	second	leap second
li	-	unit vector or direction of the incident or pre-refraction light ray
limll	-	li - ll
ll	-	direction of the light ray after leaving the target system
llmle	-	ll - le
lo	-	direction of the light ray at the telescope before being observed
lomli	-	lo-li
MO	km; km/s	Position and velocity vector from the Moon to the observer
OffAbe	arcsecond	offset due to aberration in (dRA*, dDEC)
OffAbe1	arcsecond	offset due to first-order aberration
OffAbe2	arcsecond	offset due to second-order aberration
OffAll	arcsecond	offset due to all effects
OffLenS	arcsecond	offset due to all lensing in the solar system
OffLenT	arcsecond	offset due to all lensing in target system
OffRef	arcsecond	offset due to atmospheric refraction
OL	-	a list of observer to solar system body (lens) vectors
OutBT	-	a list of outputs from binary models
rBT	au	position vector from TSB to T
RBT	au	length of rBT
ref	rad	refraction vector
Ref	rad	refraction angle
rOB	pc	position vector from the observer to the TSB
rOC	pc	position vector from the observer to the companion (C)
Roemer1	second	first order Roemer delay in the solar system
Roemer2	second	second order Roemer delay in the solar system
Roemer3	second	third order Roemer delay in the solar system
RoemerOrder	second	a combined list of Roemer1, Roemer2 and Roemer3
RoemerSB	second	Roemer delay using SB rather than ST as the reference direction (only for comparison)
RoemerSolar	second	total Roemer delay in the solar system
RoemerT2	second	Roemer delay calculated using the TEMPO2 method (including the total effects and effects for different terms)
RoemerTarget	second	Roemer delay in the target system
rOT	pc	position vector from the observer to the target
rSB	pc	position vector from SSB to TSB
rSC	pc	position vector from SSB to the companion
rST	pc	position vector from SSB to the target
rTC	au	position vector from the target to the companion

variable	unit	meaning
RvBT	m/s	radial velocity for TSB to T
RvGO	m/s	radial velocity for geocenter to observer
RvgsO	m/s	general and special relativistic effect on RV at the observatory or in the solar system
RvgT	m/s	general and special relativistic effect on RV in the target system
RvlO	m/s	lensing RV in the solar system
RvLocal	m/s	all RV effects in the solar system
RvlT	m/s	lensing RV in the target system
RvRemote	m/s	all RV effects in the target system
RvSB	m/s	RV due to motion of TSB w.r.t. SSB
RvSG	m/s	RV due to motion of the geocenter w.r.t. SSB
RvSO	m/s	RV due to motion of the observer w.r.t. SSB
RvsT	m/s	special relativitistic effect on RV in the target system
RvST	m/s	RV due to motion of the target w.r.t. SSB
RvTot	m/s	total RV
RvTropo	m/s	tropospheric RV
SB	pc; au/yr	position and velocity vectors from the SSB to TSB
SG	km; km/s	position and velocity vectors from the SSB to the geocenter
ShapiroEarth	second	Shapiro delay due to Earth
ShapiroJupiter	second	Shapiro delay due to Jupiter
ShapiroMars	second	Shapiro delay due to Mars
ShapiroMercury	second	Shapiro delay due to Mercury
ShapiroMoon	second	Shapiro delay due to Moon
ShapiroNeptune	second	Shapiro delay due to Neptune
ShapiroPlanet	second	a combined list of Shapiro delays due to solar system objects
ShapiroSaturn	second	Shapiro delay due to Saturn
ShapiroSolar	second	Shapiro delay in the solar system
ShapiroSun	second	Shapiro delay due to Sun
ShapiroTarget	second	Shapiro delay in the target system
ShapiroUranus	second	Shapiro delay due to Uranus
ShapiroVenus	second	Shapiro delay due to Venus
SO	km; km/s	position and velocity vectors from the SSB to the observer
SolarDef	rad	deflection angle (vector) due to lensing in the solar system
SolarDefList	rad	a list of deflection angles due to lensing by solar system objects
TargetDelay	second	total delay in the target system
tauE	JD	proper emission time
tB	JD	coordinate light arrival time at TSB
TDBmTTgeo	second	TDB-TT at the geocenter
TropoDelay	second	tropospheric delay
TropoDelayT2	second	tropospheric delay calculated using uSB(t=tpos) or ub (see paper) as the reference direction as done in TEMPO2t
tS	JD	same as BJD[TCB]; coordinate ligth arrival time at SSB
U	rad	eccentric anomaly
uBT	-	unit vector for rBT
uo	-	observed direction of the target
uOB	-	unit vector for rOB
uOC	-	unit vector for rOC
uommlo	-	uo+lo
uommlo1	-	uo+lo1
uommlo2	-	uo+lo2
uommlo3	-	uo+lo3
uOT	-	unit vector for rOT

variable	unit	meaning
uSB	-	unit vector for rSB
uSB.T2	-	uSB calculated using the TEMPO2 method (ignoring third order effects)
uST	-	unit vector for rST
VacuumIS	-	vacuum delay in interstellar medium
vBT	au/yr	velocity of T w.r.t. TSB
vGO	km/s	velocity of the observer w.r.t. the geocenter
vOB	au/yr	velocity of TSB to the observer
vOT	au/yr	velocity of target to the observer
vSB	au/yr	velocity of TSB to SSB
vST	au/yr	velocity of the target to SSB
xp	rad	parameter for polar motion of the Earth
yp	rad	parameter for polar motion of the Earth
ZB	-	barycentric correction of Doppler shift
ZBwe	-	barycentric correction of Doppler shift using Wright & Eastman 2014 method
Zcomb	-	combined list of all doppler shifts
ZenIn	rad	zenith angle
ZenInT2	rad	zenith angle using uSB(t=tpos) or ub (see paper)
zenith	rad	zenith vector
ZgO	-	doppler shift due to general relativistic effect in the solar system
ZgsO	-	doppler shift due to relativistic effects in the solar system
ZgsO.de	-	doppler shift due to relativistic effects in the solar system calculated using JPL ephemerides
ZgSS	-	combined list of gravitational doppler shifts due to solar system objects
ZgsT	-	doppler shift due to relativistic effects in the target system
ZgTk	-	doppler shift due to general relativistic effect in the target system
ZkpO	-	doppler shift due to parallax delay in the solar system
ZkpT	-	doppler shift due to parallax delay in the target system
Zlensing	-	combined list of doppler shifts due to lensing by solar system objects
ZlO	-	doppler shift due to solar system lensing
Zlocal	-	local doppler shift
ZlT	-	doppler shift due to target system lensing
Zremote	-	local doppler shift
ZsO	-	special relativistic doppler shift in the solar system
ZSO	-	doppler shift due to the motion of SSB w.r.t. the observer
ZsT	-	special relativistic doppler shift in the target system
ZST	-	doppler shift due to the motion of target w.r.t. SSB
ZST0	-	doppler shift due to the motion of target w.r.t. SSB using uSB.T
ZST0	-	doppler shift due to the motion of target w.r.t. SSB using uSB.T
zTDBmTTgeo	-	doppler shift corresponding to the time derivative of TDB-TT at the geocenter
zTDBmTTobs	-	doppler shift corresponding to the time derivative of the observer term in TDB-TT
zTDBmTTobsR	-	zTDBmTTobs due to rGO
zTDBmTTobsV	-	zTDBmTTobs due to vGO
Ztot	-	total doppler shift
Ztropo	-	tropospheric doppler shift

4 Examples

4.1 Simulation of single star systems

PEXO can be used to simulate the timing, RV and astrometry variation of a single star. PEXO will automatically find astrometry data from Simbad if it is not given manualy. To explain the output of PEXO, tau Ceti is simulated using the following commandline:

```
Rscript pexo.R -p HD10700 -t '2450000 2460000 10' -i 'ESO' -c 'TAR'
```

In the output of PEXO, the various timing, RV and astrometric effects are printed. Summary plots for these effects are saved as pdfs with names of `../results/AllTimes_HD10700_timing_kepler_Ntime1001.pdf`, `../results/absolute_HD10700_astrometry_kepler_Ntime1001_none.pdf`, and `../results/paper_HD10700_RV_kepler_`. The user can also choose which variables to be saved in an output file with default name of `out_pexo.txt`. The user can specify `-o` and `-v` to define the output file name and variable names, respectively. For example, if the user is interested in barycentric correction of a star, he/she could add `-v 'BJDtdb ZB'` to the commandline and then get BJDtdb and ZB from the output file. The barycentric RV is ZB*c where c is the speed of light.

4.2 Simulation of stars with companions

The main advantage of PEXO is to model the timing, RV and astrometry for binaries to a high precision. alpha Cen A and B are a good exmample to demonstrate this. For exmaple, the following commandline

```
Rscript pexo.R -p HD128620 -t '2450000 2460000 10' -i 'PFS' -c 'TAR' -C 1
```

will simulate alpha Cen A and B from JD2450000 to JD2460000 by a time step of 10 days. The instrument is PFS and the components in the simulation include timing (T), astrometry (A), and RV (R). As for the case of single stars, one will get summary plots and magnitudes of various effects as well as output ascii file (named out_pexo.txt by default).

4.3 Fitting for single star systems

For emulation/simulation mode, one cannot optimize the astrometric and orbital parameters. By fitting these parameters to various data, one is able to find the optimal astrometric and orbital solution. To do that, the data files for fitting should be named according to the following format if HD10700 is the primary star and xxx is an instrument name:

```
Timing data (typically is data for time delay): HD10700_xxx.delay
RV data: HD10700_xxx.rv
Absolute astrometry data: HD10700_xxx.abs
Relative astrometry data: HD10700_xxx.rel
```

For timing data, there are at least two columns: JD[UTC], delay [s], (delay error [s]). For RV data, there are three columns: JD[UTC], RV [m/s], RV error [m/s]. Note that the time and RV in RV data should not be barycentrically corrected. For absolute and relative astrometry data, there are at least five columns: JD[UTC], ra [deg], ra error [mas], dec [deg], dec error [mas], (lambda [μm]). Lambda is the wavelength of an ground-based astrometric measurement. If not given, PEXO will assumes 0.55 μm wavelength which will be used to determine the amount of atmospheric refraction.

Proxima Cen or GJ551 is taken as an example to explain how to use the PEXO fitting mode. For example, the following commandline

```
Rscript pexo.R -m fit -p GJ551 -N 100
```

or you can specify the output Robj name, e.g.

```
Rscript pexo.R -m fit -p GJ551 -N 100 -o 'test.Robj'
```

will launch 4 MCMC and each has a length of 100. The pexo outputs (exclude the variation of barycentrically corrected RV files) are explained as follows:

file name	meaning
../results/GJ551_barycorrected.rv	Barycentrically corrected combined RV
../results/GJ551_0companion_llmax-2810322_N100_einsteinTRUE.pdf	Summary plots for the model prediction (red) and data (black) as well as residuals and mcmc trace plots etc.
../results/GJ551_0companion_llmax-2810322_N100_einsteinTRUE_fancy.pdf	Fancy plots for PEXO-simulated optimal fit to raw data as well as small panels showing residuals
../results/GJ551_0companion_llmax-2810322_N100_einsteinTRUE.Robj	All outputs of PEXO are saved as an R object (xxx.Robj). The path of this file can be defined by the -o input parameter.

In the Robj file, the MCMC related variables are explained as follows.

variable name	meaning
Data	A data frame saving all input data, first column: UTC time; second column: RV[m/s], or delay [second], or RA [deg], or dRA [mas]; third column: error of the second column; fourth column: NA for RV and delay data and DEC[deg] or dDEC[mas] for absolute and relative astrometry respectively; fifth column: error of fourth column; sixth column: star name; seventh column: data type; eighth column: instrument; ninth column: wavelength[μm] for astrometry data
model	Model prediction at the raw data epochs, the columns have the same meanings.
pred	Model prediction at simulated epochs (typically with higher cadence and with constant time steps sampling over the whole data timespan), the columns have the same meanings.
ParStat	Statistics of parameters infered from MCMC posterior samples. Columns are model parameters and rows are the statistics for them, including xopt: optimal value at the maximum a posteriori, x1per: 1% quantile; x99per: 99% quantile; x10per: 10% quantile; x90per: 90% quantile; xminus.1sig: xopt-1sigma; xplus.1sig: xopt+1sigma; and other statistics are easy to understand. The parameters of `raOff [mas]`, `decOff [mas]`, `pmraOff [mas/yr]`, `pmdecOff [mas/yr]`, `plxOff [mas]` are offsets added to the initial astrometry of the barycenter of the target system. The parameters of `logjitterRv.star.instrument` and `bRv.star.instrument` are log jitter and intercept for a given instrument and star. For binary or star-companion system, the orbital parameters are also given with the number of companions added to the end of each parameter name. In specific, `logmC1` is the log mass of the first companion in units of solar mass; `logP1` is the log orbital period in units of day; `e1` is eccentricity; `I1` is inclination in radiant; `omegaT1` is the primary star argument of periastron in radiant; `Omega1` is the longitude of ascending node in units of radiant; `Mo1` is the mean anomaly in units of radiant.

4.4 Fitting for stars with companions

To fit a binary model to the data, you can run the following commandline (e.g., Kruger 60 or HD239960)

```
Rscript pexo.R -m fit -p HD239960 -N 100 -C 1
```

Then you will get similar output as for the case of single stars.

5 Run PEXO using shell script

A simple shell wrapper is included for convenience. The arguments are identical to `pexo.R`, type `./pexo.sh --help` so see help.

To run PEXO via this script, you need to set an environment variable `$PEXODIR` to a path to the PEXO repository. It is also recommended to create an alias for this script to run it from anywhere in the terminal. To do that, add

```
export PEXODIR=/example/path/to/pexo
alias pexo="/example/path/to/pexo/pexo.sh"
```

to your `~/.bashrc` or `~/.bash_profile` if you're using bash, or

```
setenv PEXODIR /example/path/to/pexo
alias pexo /example/path/to/pexo/pexo.sh
```

to `~/.tcshrc` if you're using tcsh. You'll need to open a new terminal or type `source ~/.bashrc` / `source ~/.tcshrc` to apply this. You may also `source ~/.bash_profile` to permanently save the settings. Note that the path to pexo should be absolute. Then you can open a new terminal window to use PEXO everywhere in your computer.

For example, you have the following two options to run a simulation of Tau Ceti.

You may either go to the `pexo/code` directory and run

```
Rscript pexo.R -p HD128620 -t '2450000 2460000 10' -i 'PFS' -c 'TAR' -C 1
```

or run the following shell script in your current directory by providing paths for timing and parameter files

```
pexo -p HD128620 -t '2450000 2460000 10' -i 'PFS' -c 'TAR' -C 1
```

By running the above command line, PEXO will look for the parameter and data files in the ../input/ directory and save output file if you specify the `-v` and `-o` arguments.

6 Future development

PEXO v2 is able to emulate a system or fit a Keplerian model to timing, astrometry and RV data sets. A python wrapper are also developed for python users. PEXO v3 will provide functionality for pulsar timing and gravitational wave searches. Feedback from PEXO users and contribution from the astronomical community are appreciated and are important to improve the software.