# PEXO v0.1.0

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# 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  $\mu$ m/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 by running

Rscript install\_dependencies.R

(might require su privileges to be installed): or just install them manually using install.packages('xxx') 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 -c TR -t file.tim -p file.par

The commandline 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]	
-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	par	Parameter file: parameters for models, observatory, for	
		Keplerian/binary motion [mandatory]	
-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]	

Since the astrometry and radial velocity modeling depends on the the output of timing model, T should always be included in the  $\neg c$  or  $\neg \neg c$ omponent argument.

## 3.2 Input timing data

The -t argument is mandatory 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 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.

## 3.3 Input parameters

The other mandatory argument is the parameter file which provides the values of input parameters. We list these parameters and their meanings in the following table. The bold-faced values are default ones. If there is no default value for a given parameter, it should be given manually and an example value is provided for reference in the options or examples column.

parameter	$\operatorname{unit}$	options or examples	meaning
name	-	First five characters of parameter file name, any string	name of the target
RefType	-	none, refro, refco, refcoq	computation method for atmospheric refraction
EopType	-	<b>2006</b> , 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	_	<b>430</b> , 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
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	_	DDGR, kepler	binary model
ellipsoid	-	<b>WGS84</b> , GRS80, WGS72	ellipsoidal (normal) Earth Gravitational Model
epoch	JD or MJD	2448349.06250	epoch when the astrometry and position of the target is measured
observeatory	-	CTIO	observatory name
xtel	metre	1814985.3	geocentric position of the telescope in the International Terrestrial Reference Frame (ITRF)
ytel	$_{ m metre}$	-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	$_{ m millibar}$	1013.25	pressure at the telescope
$^{\mathrm{rh}}$	-	0.1	relative humidity at the observer (range 0-1)
wl	$\mu\mathrm{m}$	0.5	effective wavelength of the source
tlr	K/metre	<b>0.0065</b> , any value>0	Temperature lapse rate in the troposphere
g	1.6	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 747 1700009	declination (DEC) of the barycenter (TSB)
plx pmre	mas	747.1700008	parallax of the barycenter (TSB)
pmra pmdec	$\frac{\text{mas/yr}}{\text{mas/yr}}$	-3649.4980522 624.7691720	proper motion in RA of the barycenter (TSB) proper motion in DEC of the barycenter (TSB)
rv	$\mathrm{km/s}$	-22.3929553	radial velocity of the barycenter (TSB)

parameter	$\operatorname{unit}$	options or examples	meaning
aT	au	10.80332	semi-major axis of the barycentric motion of the target
P e	year -	79.929 0.5208	orbital period of the target eccentricity
I	degree	79.32	inclination
omegaT Omega	degree degree	52.006 205.064	argument of periatron longitude of ascending node
Тр	$_{ m JD}$ or $_{ m MJD}$	2435328.96	periastron epoch

In the above table, from name to observatory are non-fitable parameters which are mainly used for solar system ephemeris and the modeling of Earth rotation. The other parameters are fitable although we have not implemented the fitting part of PEXO. epoch is the time when the position and astrometry of the target system is measured. It is tpos defined in the PEXO paper.

#### 3.3.1 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 alt (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.

#### 3.3.2 Binary or Keplerian model parameters

The five orbital parameters for a binary motion should be specified if the target system is a binary. If BinaryModel is none, PEXO treats the target system as a single-star system. If BinaryModel is DDGR or kepler, PEXO will look for Keplerian parameters. The target is denoted by T and companion by C. The mass of T is mT, the mass of C is mC and the mass of the whole system is mTC. Two of them should be given for binary simulations. The semi-major axis of the barycrentric orbit of T is aT, that of C is aC, and that of the binary orbit of C with respect to T is aTC. Either the orbital period P or one of the semi-major axes aT, aC, or aTC should be given to determine the binary orbit. If one of them is given, the other parameters will be derived. Either the periastron epoch Tp, or the mean anomaly MO at the reference epoch TO, or the primary transit epoch Tc should be given to determine the binary orbit. If one of them is given, the others will be derived.

#### 3.4 Output

#### 3.4.1 Output variables

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

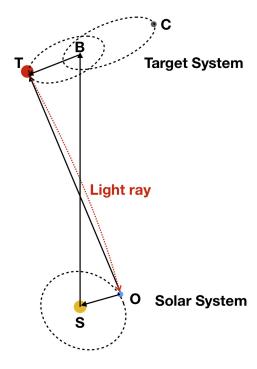


Fig. 1. Illustration of a light ray emitted from the target (T) and observed by the observer (O). The target system is composed of the target (T) and its companion (C). The binary barycenter is denoted by B. The observer is in the solar system with a barycenter at S.

There are outputs from four functions in PEXO:

```
OutBary <- time_Utc2tb(utc,Par)</pre>
```

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

```
OutTime <- time_Ta2te(OutBary,Par)</pre>
```

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(OutBary,OutTime,Par,Mlens=Par$mC,component='T')
OutAstroC <- astro_FullModel(OutBary,OutTime,Par,Mlens=Par$mT,component='C')</pre>
```

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(OutBary,OutTime,Par)</pre>
```

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  $\neg v$  are specified in the command line.

We list the output variables in  ${\tt OutAll}$ , 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	$\operatorname{rad}$	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	-	$\mathrm{dTCB}/\mathrm{dTT}$
$\mathrm{d}\mathrm{TDB}.\mathrm{d}\mathrm{TT}$	-	$\mathrm{dTDB}/\mathrm{dTT}$
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
$\operatorname{emrat}$	_	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
D 1 T	/	(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
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
ID.	ID	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

variable	unit	meaning
limll	-	li - ll
11	-	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
Roemerob	весона	(only for comparison)
RoemerSolar	second	total Roemer delay in the solar system
RoemerT2	second	Roemer delay calculated using the TEMPO2 method (including the
100011101 1 2	become	total effects and effects for different terms)
RoemerTarget	second	Roemer delay in the target system
rOT	рс	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
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
10,820	111/5	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 13B w.r.t. SSB
RvSO	m/s	RV due to motion of the geocenter 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	$\mathrm{m/s}$	tropospheric RV

SB pc; au/yr position and velocity vectors from the SSB to TSB (mr, km/s) second Shapiro delay due to Earth SSBapiro delay due to Mars Shapiro delay due to More Shapiro delay due to Noptune Shapiro Shapiro Shapiro Shapiro delay due to Shapiro delay	variable	unit	meaning
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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 deflection angle (vector) due to lensing in the solar system of deflection angle (vector) due to lensing in the solar system of deflection angles due to lensing by solar system objects 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 TropoDelay 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 light 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+lo1 uommlo1 - uo+lo1 uommlo2 - uo+lo2 uommlo3 - uo+lo3 uOT - unit vector for rSB uSB.T2 - unit vector for rSB uSB calculated using the TEMPO2 method (ignoring third order effects) uST VacuumIS - velocity of T w.r.t. TSB vGO km/s velocity of TSB to the observer vSB au/yr velocity of TSB to the observer vSB au/yr velocity of TSB to SSB xp rad parameter for polar motion of the Earth yp rad parameter for polar motion of the Earth Darycentric redshift	ShapiroSolar	second	Shapiro delay in the solar system
ShapiroVenus 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 deflection angle (vector) due to lensing in the solar system 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 TropoDelayT2 second tropospheric delay calculated using uSB(t=tpos) or ub (see paper) as the reference direction as done in TEMPO2t same as BJD[TCB]; coordinate light 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 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 Tw.r.t. TSB vGO km/s velocity of TsB to the observer vOT au/yr velocity of TsB to the observer vSB au/yr velocity of TsB to SSB vST xp rad parameter for polar motion of the Earth yp rad parameter for polar motion of the Earth Darycentric redshift ZB - barycentric redshift zB barycentric redshift using uSB.T2	ShapiroSun	second	Shapiro delay due to Sun
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SolarDef SolarDefList rad SolarDefList Second SolarDefList Second SolarDefList SolarDefList Second SolarDefList	ShapiroVenus	second	Shapiro delay due to Venus
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           TBBmTTgeo         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 light arrival time at SSB           U         rad         eccentric anomaly           uBT         -         unit vector for rBT           u0         -         observed direction of the target           uOB         -         unit vector for rOB           uOC         unit vector for rOC           uommlo         uo+lo           uommlo1         -           uoT         -           uSB         -           uSB         -           uSB         -           uSB         -           uSB         -           uSB	SO	km; km/s	position and velocity vectors from the SSB to the observer
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$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	TropoDelayT2	second	
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uOT-unit vector for rOTuSB-unit vector for rSBuSB.T2-uSB calculated using the TEMPO2 method (ignoring third order effects)uST-unit vector for rSTVacuumIS-vacuum delay in interstellar mediumvBTau/yrvelocity of T w.r.t. TSBvGOkm/svelocity of the observer w.r.t. the geocentervOBau/yrvelocity of TSB to the observervSBau/yrvelocity of target to the observervSTau/yrvelocity of TSB to SSBxpradparameter for polar motion of the Earthypradparameter for polar motion of the EarthZB-barycentric redshiftZB-barycentric redshift using uSB.T2	uommlo2	-	uo+lo2
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 redshift  ZBt - barycentric redshift using uSB.T2	uommlo3	-	uo+lo3
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 redshift  ZBt - barycentric redshift using uSB.T2	uOT	-	unit vector for rOT
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 redshift  ZBt - barycentric redshift using uSB.T2		-	
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 redshift  ZBt - barycentric redshift using uSB.T2	uSB.T2	-	uSB calculated using the TEMPO2 method (ignoring third order
VacuumIS  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 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 redshift  ZBt  -  barycentric redshift using uSB.T2			effects)
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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 redshift ZBt - barycentric redshift using uSB.T2	vOT		velocity of target to the observer
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 redshift ZBt - barycentric redshift using uSB.T2	vSB	, -	
xpradparameter for polar motion of the Earthypradparameter for polar motion of the EarthZB-barycentric redshiftZBt-barycentric redshift using uSB.T2	vST	, -	
yp rad parameter for polar motion of the Earth ZB - barycentric redshift ZBt - barycentric redshift using uSB.T2	xp	, -	
ZB - barycentric redshift ZBt - barycentric redshift using uSB.T2		$\operatorname{rad}$	
ZBt - barycentric redshift using uSB.T2		-	
	ZBt	-	
	Zcomb	-	combined list of all doppler shifts

variable	unit	meaning
ZenIn	rad	zenith angle
ZenInT2	$\operatorname{rad}$	zenith angle using uSB(t=tpos) or ub (see paper)
zenith	$\operatorname{rad}$	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 Use Tau Ceti as an example to compare PEXO with previous packages

The following commandline will simulate the Tau Ceti system over 10000 days with a time step of 10 days. It will reproduce the right panel of figure 11 in the paper.

Rscript pexo.R -m emulate -c TR -t ../input/mjd42000to52000by10day.tim -p ../input/TC\_Fig11b.par The following output pdf files correspond to the figures in the PEXO paper

- ../results/timing\_E10original\_TauCeti\_tempoFB90\_DE430\_ttt2tdbeph\_tempo\_par4\_none.pdf
  - left panel of Figure 10
  - modified utc2bjd.pro compared with original utc2bjd.pro routine (with bug in parallax delay) based on Eastman  $2010\,$
- ../results/timing\_TauCeti\_tempoFB90\_DE430\_ttt2tdbeph\_e10\_par4\_none\_originalTRUE.pdf
  - middle panel of Figure 10
  - timing bias caused by the assumption of zero proper motion in utc2bjd.pro
- ../results/pexot\_TauCeti\_tempoFB90\_DE430\_ttt2tdbeph\_e10\_par4\_none\_originalTRUE.pdf

- right panel of Figure 10
- timing bias in TEMPO2 due to ignoring third-order Roemer delay and bug in planet shapiro delay
- ../results/paper\_RV\_TauCeti\_tempoFB90\_DE430\_ttt2tdbeph\_none.pdf
  - right panel of Figure 11
  - barycentric velocity computed using PEXO compared with TEMPO2
- ../results/Sun\_TauCeti\_tempoFB90\_DE430\_ttt2tdbeph\_par4\_none.pdf
  - topleft panel of Figure 8
  - shapiro delay due to the Sun
- ../results/Jupiter\_TauCeti\_tempoFB90\_DE430\_ttt2tdbeph\_par4\_none.pdf
  - topright panel of Figure 8
  - shapiro delay due to Jupiter
- ../results/Saturn\_TauCeti\_tempoFB90\_DE430\_ttt2tdbeph\_par4\_none.pdf
  - bottomleft panel of Figure 8
  - shapiro delay due to Saturn
- ../results/Uranus\_TauCeti\_tempoFB90\_DE430\_ttt2tdbeph\_par4\_none.pdf
  - bottomright panel of Figure 8
  - shapiro delay due to Uranus

The left panel of figure 11 can be recovered by the following command line. Rscript pexo.R -m emulate -c TR -t ../input/mjd42000to52000by10day.tim -p ../input/TC\_Fig11a.par

The output pdf file ../results/paper\_pexo\_vs\_T2\_TauCeti\_tempoFB90\_DE430\_ttt2tdbeph\_Tstep1d\_none.pdf will show a few  $\mu$ m/s numerical radial velocity difference between PEXO and TEMPO2.

# 4.2 Comparison of JPL ephemerides

The following commandline will compare various ephemerides and recover Figure 9 in the paper. There are only DE430 and DE405 ephemerides in the github repository and thus only they will be compared. One can download a JPL ephemerides using source download\_ephemerides.sh XXX where XXX could be any JPL ephemerides such as 438, 438t, 414, .... The ephemerides would be downloaded into the pexo/data/directory.

Rscript compare\_ephemeris.R -m emulate -c TR -t ../input/mjd42000to52000by10day.tim -p ../input/TC\_Fig1

- ../results/ephemeris\_comparison\_BJDtdb\_tttdbFB01\_FALSE.pdf
  - left panel of Figure 9
  - comparison of BJD[TDB] calculated using various JPL ephemerides
- ../results/ephemeris\_comparison\_pos\_tttdbFB01\_FALSE.pdf
  - middle panel of Figure 9
  - comparison of  $r_{SG}$
- ../results/ephemeris\_comparison\_vel\_tttdbFB01\_FALSE.pdf
  - right panel of Figure 10
  - comparison of  $v_{SG}$

#### 4.3 $\alpha$ Centauri A and B

The following commandline will simmulate the alpha Centauri system from MJD42000 to MJD52000 by a step of 10 days.

Rscript pexo.R -m emulate -c TA -t ../input/gaia80yrby10day.tim -p ../input/ACAgaia.par

- ../results/absolute\_alphaCenA\_astrometry\_DDGR\_dt10day\_Ntime2923\_refro.pdf
  - Figure 14
  - absolute astrometry of alpha Cen A
- ../results/relative\_alphaCenA\_astrometry\_DDGR\_dt10day\_Ntime2923\_refro.pdf

- Figure 15
- relative astrometry of alpha Cen B with respect to A

The following commandline will simulate the radial velocity variation of alpha Centauri A.

Rscript pexo.R -m emulate -c TR -t ../input/hip80yrby10day.tim -p ../input/ACAhip.par

The file ../results/paper\_alphaCenA\_RV\_DDGR\_dt10day\_Ntime2923\_refro.pdf is the same as Figure 17 in the paper and shows the decomposition of the radial velocity into multiples components due to various effects.

## 4.4 PSR J0740+6620

Recently the Shapiro delay of PSR J0740+6620 is measured to a high precision by Cromarti et al. 2019. PEXO can produce their results by using the reported orbital parameters in the following commandline.

Rscript pexo.R -c T -t '2456640.5 2458462.5 0.5' -p ../input/PSR\_J0740+6620.par

The output pdf ../results/PSRJ0740+6620\_shapiro.pdf will predict a Shapiro delay matching the one shown in the paper.

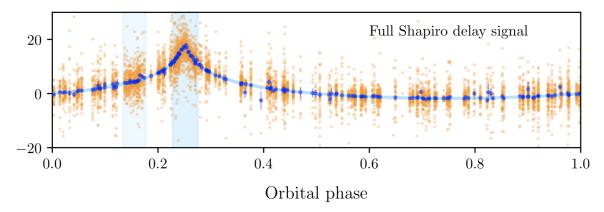


Fig 2. Shapiro delay of PSR J0740+6620 measured through pulsar timing by Cromarti et al. 2019

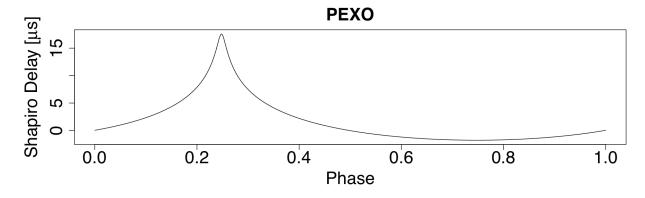


Fig 3. Shapiro delay of PSR J0740+6620 simulated by PEXO using parameters from Cromarti et al. 2019

# 4.5 $\delta$ Del (HD197461)

 $\delta$  Del has a well-determined orbit based on astrometric and RV data from Gardner et al. 2018. By using the following commandline, one can reproduce the binary orbit.

Rscript pexo.R -c T -t '38300 57600 100' -p ../input/HD197461.par

Panel P8 in the output file ../results/relative\_HD197461\_astrometry\_DDGR\_dt100day\_Ntime194\_none.pdf reproduces figure 3 in the original paper.

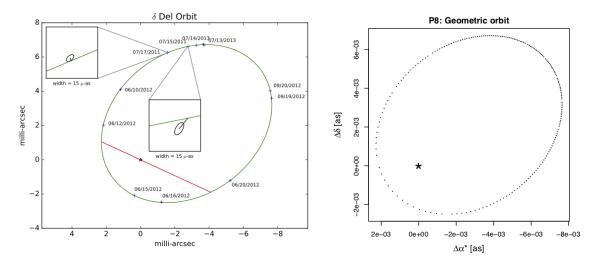


Fig. 4. The left panel shows the orbit of  $\delta$  Del determined by Gardner et al. 2018 while the right panel shows the orbit simulated by PEXO using the parameters from Gardner et al. 2018.

# 5 Future development

PEXO v0.1.0 only implement the emulation part of the software. The fitting part will soon be implemented. A python wrapper would also be developed. A R Shiny application will be developed for some functions of PEXO such as barycentric correction and UTC to TDB and to BJD conversions.