prototype_johan_method

March 14, 2017

This notebook works out the basic components that are required to implement the Fourier method discussed in Samsing (2015).

```
In [1]: import numpy as np
        import matplotlib.pyplot as plt
        import batman
        import os
        %matplotlib inline

In [2]: seedn = 1
        np.random.seed(seedn)

        # make a fake kepler quarter, in relative flux units, with gaussian
        # errors, and transits injected.
        mintime = 5+np.random.rand()
        maxtime = 94+np.random.rand()
        exp_time_minutes = 29.423259
        exp_time_days = exp_time_minutes / (24.*60)
        times = np.arange(mintime, maxtime, exp_time_days)

        # drop 5% of data points (e.g. quality flags).
        n_to_drop = int(len(times)/20)
        todrop = np.random.random_integers(0, len(times), size=n_to_drop)
        times = np.delete(times, todrop)

        # be nice with the noise...
        flux_baseline = np.ones_like(times)
        flux_noise = np.random.normal(loc=0.0, scale=0.001, size=np.size(times))

        params = batman.TransitParams()
        P_b = 10+np.random.rand()
        t0 = np.random.uniform(min(times), min(times)+P_b)
        params.t0 = t0
        params.per = P_b                    #orbital period
        params.rp = (0.01)**(1/2.)          #planet radius (in units of stellar ra
        params.a = 15.                      #semi-major axis (in units of stellar
        params.inc = 87.                    #orbital inclination (in degrees)
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params.ecc = 0.                          #eccentricity
params.w = 90.                           #longitude of periastron (in degrees)
params.u = [0.1, 0.3]                    #limb darkening coefficients
params.limb_dark = "quadratic"           #limb darkening model

ss_factor = 10
m = batman.TransitModel(params,
                        times,
                        supersample_factor = ss_factor,
                        exp_time = exp_time_days)
flux_to_inj = m.light_curve(params) - 1.

fluxs = flux_baseline + flux_noise + flux_to_inj
fluxs = (fluxs - np.median(fluxs)) / np.median(fluxs)
# get systematically wonkily reported errors
errs = flux_noise * (1+0.02*np.random.rand(np.size(flux_noise)))

τ_i = t0
N_transits = int(np.floor((max(times) - min(times))/P_b))
τ_f = t0 + N_transits*P_b
T_w = τ_f - τ_i

times_cut = times[(times < τ_f) & (times > τ_i)]
fluxs_cut = fluxs[(times < τ_f) & (times > τ_i)]
errs_cut = errs[(times < τ_f) & (times > τ_i)]

# Now that we have the times, fluxs, and errs, we want to separate the sign
# Note, per the plots way below, that the actual times at the data will in
#or that of the last transit, $\tau_f$.
# It's then necessary to _add in_ two (time, flux, err) points into the dat
#signals near them.
# Do so by fitting local quadratic to data points around 0.05 days to
# allow for 2 data points on either side
times_near_τi = times[(times < τ_i+0.05) & (times > τ_i-0.05)]
fluxs_near_τi = fluxs[(times < τ_i+0.05) & (times > τ_i-0.05)]
errs_near_τi = errs[(times < τ_i+0.05) & (times > τ_i-0.05)]
times_near_τf = times[(times < τ_f+0.05) & (times > τ_f-0.05)]
fluxs_near_τf = fluxs[(times < τ_f+0.05) & (times > τ_f-0.05)]
errs_near_τf = errs[(times < τ_f+0.05) & (times > τ_f-0.05)]

from scipy.interpolate import interp1d

f_near_τi = interp1d(times_near_τi, fluxs_near_τi, kind='quadratic')
f_near_τf = interp1d(times_near_τf, fluxs_near_τf, kind='quadratic')

# fine times are just for subsequent plotting and checking
finetimes_τi = np.concatenate((
               np.arange(τ_i, np.max(times_near_τi), exp_time_days/2),
```

```python
                np.arange(np.min(times_near_τi), τ_i, exp_time_days/2)
                ))
finetimes_τf = np.concatenate((
                np.arange(τ_f, np.max(times_near_τf), exp_time_days/2),
                np.arange(np.min(times_near_τf), τ_f, exp_time_days/2)
                ))
fluxs_τi_interp = f_near_τi(finetimes_τi)
fluxs_τf_interp = f_near_τf(finetimes_τf)

# these are the interpolated values that will be used
flux_interp_at_τi = f_near_τi(τ_i)
flux_interp_at_τf = f_near_τf(τ_f)

fluxs_sel = np.append(
            np.insert(fluxs_cut, 0, flux_interp_at_τi),
            flux_interp_at_τf)
times_sel = np.append(
            np.insert(times_cut, 0, τ_i),
            τ_f)
# fudge the errors for the first and last inserted selected data points
errs_sel = np.append(
            np.insert(errs_cut, 0, errs_cut[0]),
            errs_cut[-1])

# With preprocessing done, we are ready for the Samsing (2015) method
N = len(fluxs_sel) # number of data points

# Construct Samsing (2015) C, S and T matrices.
# Row index is times. Column index is frequencies (up to the Nyquist freque
C = np.zeros((N, int(np.floor(N/2))))
S = np.zeros((N, int(np.floor(N/2))))

# index-wise implementation: slow but instructive
#for i, t_i in enumerate(times_sel): # rows
#    for j, n_j in enumerate(range(1, int(np.floor(N/2)))): # cols
#        C[i,j] = np.cos(2 * np.pi * n_j * t_i / T_w)
#        S[i,j] = np.sin(2 * np.pi * n_j * t_i / T_w)

# vectorized implementation: fast and trickier
print('constructing cosine and sine matrices')
# n = {1, 2, 3, ..., floor(N/2)}
n = np.array(range(1, int(np.floor(N/2)+1)))
C = np.cos(2 * np.pi * np.outer(times_sel-τ_i, n) / T_w)
S = np.sin(2 * np.pi * np.outer(times_sel-τ_i, n) / T_w)

T = np.concatenate((C,S), axis=1)

# Solve for the least squares coefficients. Compute Fourier approxn.
```

```
        from numpy.linalg import inv
        print('beginning least squares soln for coeffs')
        R = inv(T.T @ T) @ T.T @ fluxs_sel
        print('finished inversion for least squares coeffs')
        I_approx = T @ R

        # split joined coefficient array into odd and even components
        a = R[:int(np.floor(N/2))]
        b = R[int(np.floor(N/2)):]
```

```
/home/luke/Dropbox/miniconda3/envs/sci/lib/python3.5/site-packages/ipykernel/__main
```

```
constructing cosine and sine matrices
beginning least squares soln for coeffs
finished inversion for least squares coeffs
```

```
In [3]: # N_0: number of planet orbits in data window
        N_0 = N_transits - 1
        # m = {1, 2, 3, ..., floor(N/(2*N_0))}
        m = np.array( range(1, int(np.floor(N/(2*N_0)))+1) )
        # Get the even and odd components of the reconstructed signal!
        # Initialize first:
        a_Signal = np.zeros_like(m)
        b_Signal = np.zeros_like(m)

        for ind, this_m in enumerate(m):

            selind = this_m*N_0 - 1 # -1 because python is 0-based

            # linearly interpolate over isolated peaks
            if selind <= len(a):
                a_Signal[ind] = a[selind]  - (a[selind-1] + a[selind+1])/2.
                b_Signal[ind] = b[selind]  - (b[selind-1] + b[selind+1])/2.

            # edge case: just subtract the previous one
            #elif selind > len(a):
            #    a_Signal[ind] = a[selind] - a[selind-1]
            #    b_Signal[ind] = b[selind] - b[selind-1]

        #??? not clear here :/
        I_Signal = a_Signal @ np.cos(2 * np.pi * np.outer(m, times_sel) / P_b) + \
                   b_Signal @ np.sin(2* np.pi * np.outer(m, times_sel) / P_b)

        #I_Signal = a_Signal @ np.cos(2 * np.pi * np.outer(m, times_sel-τ_i) / T_w)
        #           b_Signal @ np.sin(2* np.pi * np.outer(m, times_sel-τ_i) / T_w)
```

```
        #I_Signal = a_Signal @ np.cos(2 * np.pi * np.outer(m, times_sel-τ_i) / τ_i)
        #           b_Signal @ np.sin(2* np.pi * np.outer(m, times_sel-τ_i) / τ_i)
```

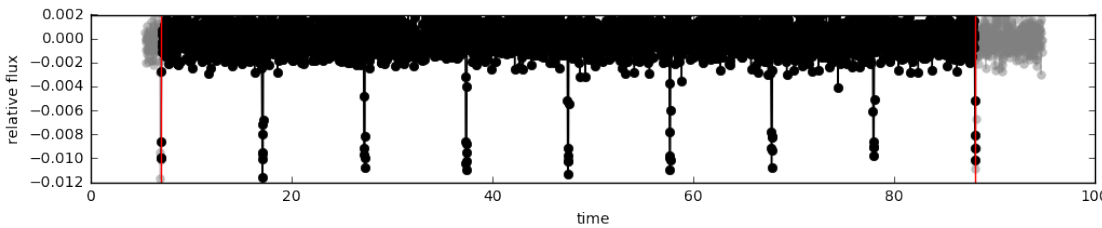
```
In [4]: print('number of data points', N)
        print('number of transits', N_transits)
        print('number of orbital periods', N_0)
        print('number of selected times (same as N?)', len(times_sel))
        print('shape of cosine matrix (rows: times, cols: freqs)', np.shape(C))
        print('shape of joined [a,b] coefficient matrix', np.shape(R))
        print('shape of joined [cosine, sine] matrix', np.shape(T))
        print('shape of split `a` coefficient matrix', np.shape(a))
        print('shape of \"signal\" Fourier coeffs', np.shape(a_Signal))
        print('shape of reconstructed signal', np.shape(I_Signal))
        print('floor(N/2N_0)', int(np.floor(N/(2*N_0))))
```

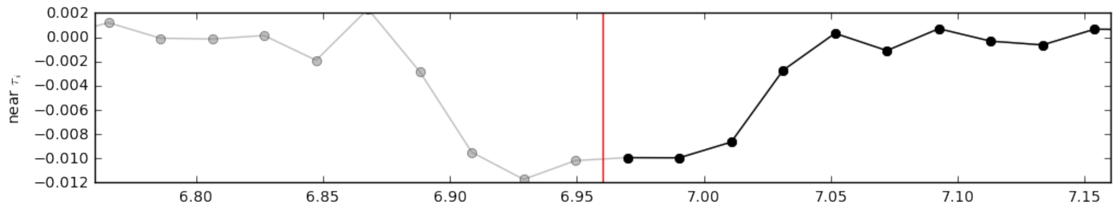
```
number of data points 3774
number of transits 8
number of orbital periods 7
number of selected times (same as N?) 3774
shape of cosine matrix (rows: times, cols: freqs) (3774, 1887)
shape of joined [a,b] coefficient matrix (3774,)
shape of joined [cosine, sine] matrix (3774, 3774)
shape of split `a` coefficient matrix (1887,)
shape of "signal" Fourier coeffs (269,)
shape of reconstructed signal (3774,)
floor(N/2N_0) 269
```

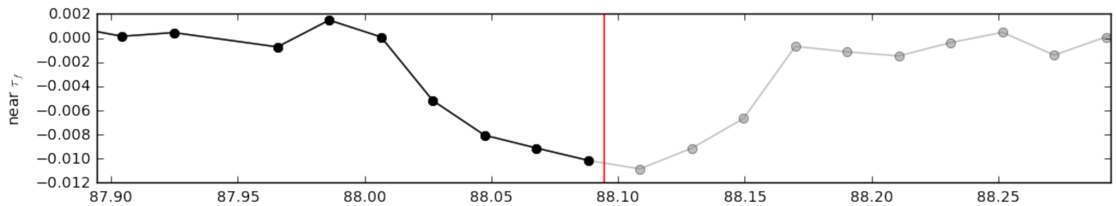
```
In [5]: ##########
        # MAIN TIMESERIES
        f, ax = plt.subplots(figsize=(12,2))
        ax.plot(times_cut, fluxs_cut, c='black', linestyle='-', marker='o', zorder=
        ax.plot(times, fluxs, c='gray', alpha=0.5, linestyle='-', marker='o', marke
        ax.vlines([τ_i, τ_f], -1, 1, color='red', zorder=2)
        ax.set_xlabel("time")
        ax.set_ylabel("relative flux")
        ax.set_ylim([-0.012, 0.002])
        f.show()

        # AT LOCAL INITIAL AND FINAL TRANSIT TIMES
        f, ax = plt.subplots(figsize=(12,2))
        ax.plot(times_cut, fluxs_cut, c='black', linestyle='-', marker='o', zorder=
        ax.plot(times, fluxs, c='gray', alpha=0.5, linestyle='-', marker='o', zorde
        ax.vlines([τ_i, τ_f], -1, 1, color='red', zorder=2)
        ax.set_ylabel(r"near $\tau_i$")
        ax.set_ylim([-0.012, 0.002])
        ax.set_xlim([τ_i-0.2,τ_i+0.2])
        f.show()
```

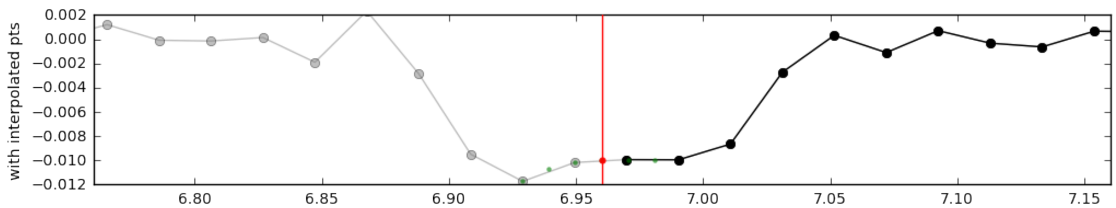
```
f, ax = plt.subplots(figsize=(12,2))
ax.plot(times_cut, fluxs_cut, c='black', linestyle='-', marker='o', zorder=
ax.plot(times, fluxs, c='gray', alpha=0.5, linestyle='-', marker='o', zorde
ax.vlines([τ_i, τ_f], -1, 1, color='red', zorder=2)
ax.set_ylabel(r"near $\tau_f$")
ax.set_ylim([-0.012, 0.002])
ax.set_xlim([τ_f-0.2,τ_f+0.2])
f.show()

# CHECKING INTERPOLATION
f, ax = plt.subplots(figsize=(12,2))
ax.plot(times_cut, fluxs_cut, c='black', linestyle='-', marker='o', zorder=
ax.plot(times, fluxs, c='gray', alpha=0.5, linestyle='-', marker='o', zorde
ax.scatter(finetimes_τi, fluxs_τi_interp, c='green', linewidth=0, marker='o
ax.scatter(τ_i, flux_interp_at_τi, c='red', linewidth=0, marker='o', s=20,
ax.vlines([τ_i, τ_f], -1, 1, color='red', zorder=3)
ax.set_ylabel("with interpolated pts")
ax.set_ylim([-0.012, 0.002])
ax.set_xlim([τ_i-0.2,τ_i+0.2])
f.show()

f, ax = plt.subplots(figsize=(12,2))
ax.plot(times_cut, fluxs_cut, c='black', linestyle='-', marker='o', zorder=
ax.plot(times, fluxs, c='gray', alpha=0.5, linestyle='-', marker='o', zorde
ax.scatter(finetimes_τf, fluxs_τf_interp, c='green', linewidth=0, marker='o
ax.scatter(τ_f, flux_interp_at_τf, c='red', linewidth=0, marker='o', s=20,
ax.vlines([τ_i, τ_f], -1, 1, color='red', zorder=3)
ax.set_ylabel("with interpolated pts")
ax.set_ylim([-0.012, 0.002])
ax.set_xlim([τ_f-0.2,τ_f+0.2])
f.show()
```

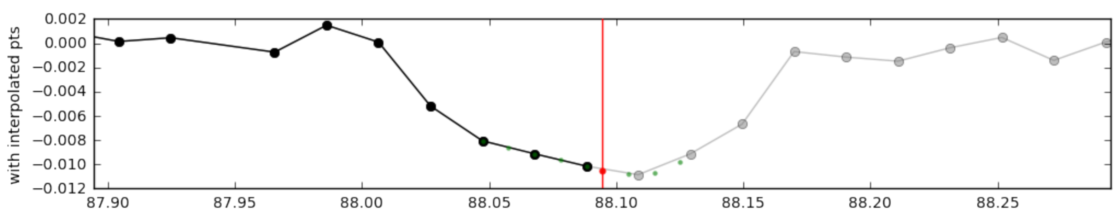
```
/home/luke/Dropbox/miniconda3/envs/sci/lib/python3.5/site-packages/matplotlib/figur
  "matplotlib is currently using a non-GUI backend, "
```





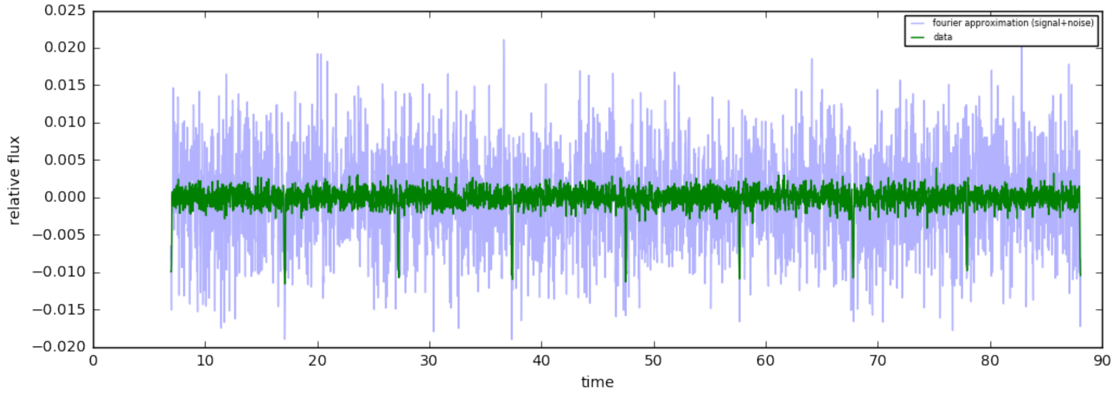






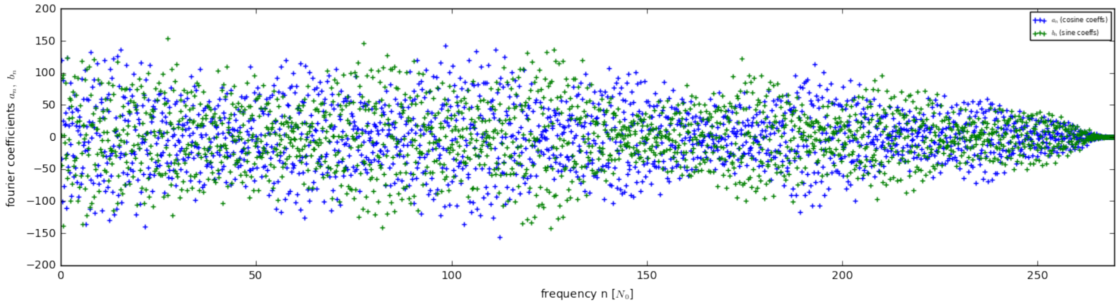
In [6]:
```
# Check that the overall approximation at least has the signal in it.
f, ax = plt.subplots(figsize=(12,4))
ax.plot(times_sel, I_approx, alpha=0.3, label='fourier approximation (signa
ax.plot(times_sel, fluxs_sel, label='data')
ax.legend(fontsize='xx-small')
ax.set(xlabel='time', ylabel='relative flux')
f.show()
```

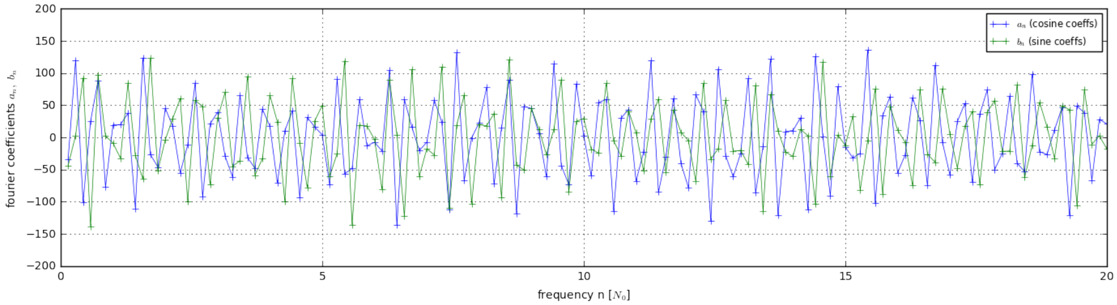
```
/home/luke/Dropbox/miniconda3/envs/sci/lib/python3.5/site-packages/matplotlib/figur
  "matplotlib is currently using a non-GUI backend, "
```




```
In [7]: # First look at full fourier range
        f, ax = plt.subplots(figsize=(14,4))
        ax.scatter(n/N_0, a, c='blue', lw=1, marker='+', label='$a_n$ (cosine coeff
        ax.scatter(n/N_0, b, c='green', lw=1, marker='+', label='$b_n$ (sine coeffs
        ax.set(xlabel='frequency n [$N_0$]',
               ylabel='fourier coefficients $a_n,\ b_n$',
               xlim=[0, max(n/N_0)])
        ax.legend(fontsize='xx-small')
        f.tight_layout()
        f.show()

        # Then look at lowest frequencies, like Samsing (2015)
        f, ax = plt.subplots(figsize=(14,4))
        ax.plot(n/N_0, a, c='blue', lw=0.5, marker='+', label='$a_n$ (cosine coeffs
        ax.plot(n/N_0, b, c='green', lw=0.5, marker='+', label='$b_n$ (sine coeffs)
        ax.set(xlabel='frequency n [$N_0$]',
               ylabel='fourier coefficients $a_n,\ b_n$',
               xlim=[0, 20])
        ax.grid(which='both')
        ax.legend(fontsize='small')
        f.tight_layout()
        f.show()
```

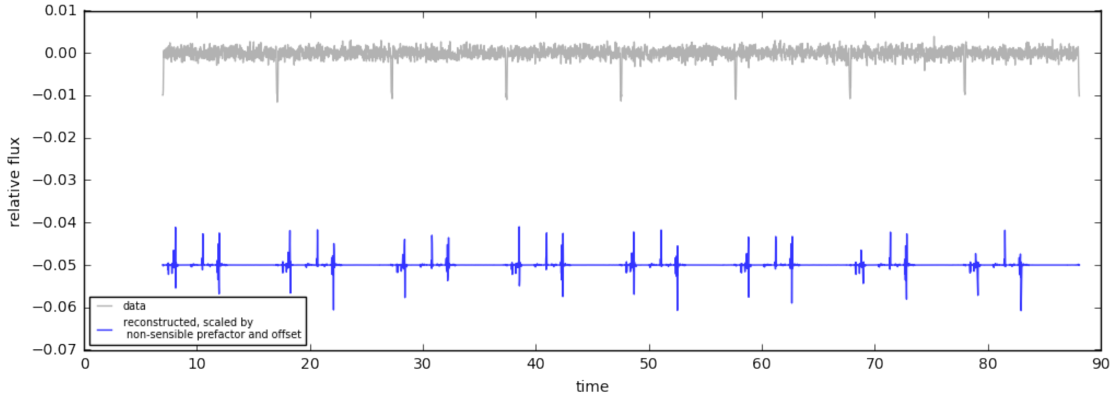
```
/home/luke/Dropbox/miniconda3/envs/sci/lib/python3.5/site-packages/matplotlib/figur
  "matplotlib is currently using a non-GUI backend, "
```






```
In [8]: # Check whether the reconstructed signal is any good.
        f, ax = plt.subplots(figsize=(12,4))
        #ax.plot(times, fluxs, c='gray', alpha=0.2, linestyle='-', marker='o', zord
        ax.plot(times_cut, fluxs_cut, c='black', linestyle='-', zorder=1, alpha=0.3
        if seedn == 2:
            pref = 1e-7
        else:
            pref = 1e-6
        ax.plot(times_sel, -0.05 + I_Signal*pref, c='blue', linestyle='-', marker=N
        ax.set_xlabel("time")
        ax.set_ylabel("relative flux")
        ax.legend(loc='best',fontsize='x-small')
        f.show()
```

```
/home/luke/Dropbox/miniconda3/envs/sci/lib/python3.5/site-packages/matplotlib/figur
  "matplotlib is currently using a non-GUI backend, "
```


0.01
0.00
−0.01
−0.02
−0.03
−0.04
−0.05
−0.06
−0.07
relative flux
0
10
20
30
40
50
60
70
80
90
time
data
reconstructed, scaled by
non-sensible prefactor and offset