Introduction to solaR

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27th September 2010

1 Introduction

The solaR package includes a set of functions which calculate the solar radiation incident on a photovoltaic generator and simulate the performance of several applications of the photovoltaic energy. The current version of this package allows the whole calculation from the global horizontal irradiation to the final productivity of grid connected PV systems and water pumping PV systems. Besides, the package includes a tool for the statistical analysis of the performance of a large PV plant composed of several systems.

This version includes several changes from the earlier version. Although an effort has been devoted in order to reduce the the external changes of the functions usage, these changes are clearly visible. These are the most important changes:

1. The package is constructed with S4 classes and methods.
2. The time series are represented thanks to the zoo package [8].
3. A lot of functions and arguments have been renamed with english words, in order to ease the understanding by international users.
4. Two new functions have been included for the statistical analysis of a PV plant composed of several systems.

2 Solar Geometry

The apparent movement of the Sun is defined with some equations included in the functions fSolD and fSolI. fSolD computes the daily apparent movement of the Sun from the Earth. This movement is mainly described (for the simulation of photovoltaic systems) by the declination angle, the sunset angle and the daily extra-atmospheric irradiation. On the other hand, fSolI computes the angles which describe the intra-daily apparent movement of the Sun from the Earth.

The next example shows these calculations for a certain day:

```
> BTd = fBTd(mode = "serie")
> lat = 37.2
> SolD <- fSolD(lat, BTd[100])
> SolI <- fSolI(SolD, sample = "hour", keep.night = FALSE)
> head(SolI)

                          w aman cosThzS     AlS     AzS    Bo0      rd
2010-04-10 06:00:00 -1.5708    1 0.07927 0.07935 -1.6758  107.8 0.01130
2010-04-10 07:00:00 -1.3090    1 0.28365 0.28760 -1.5179  385.8 0.04044
2010-04-10 08:00:00 -1.0472    1 0.47410 0.49394 -1.3472  644.9 0.06759
2010-04-10 09:00:00 -0.7854    1 0.63764 0.69143 -1.1433  867.3 0.09091
2010-04-10 10:00:00 -0.5236    1 0.76313 0.86814 -0.8742 1038.0 0.10880
2010-04-10 11:00:00 -0.2618    1 0.84202 1.00101 -0.4957 1145.3 0.12005
                         rg
2010-04-10 06:00:00 0.007935
2010-04-10 07:00:00 0.032395
2010-04-10 08:00:00 0.060379
2010-04-10 09:00:00 0.088405
2010-04-10 10:00:00 0.112414
2010-04-10 11:00:00 0.128619
```

and for a set of days:

```
> SolD <- fSolD(lat, BTd[c(10, 50, 100)])
> print(SolD)

              decl    eo     ws Bo0d       EoT
2010-01-10 -0.3847 1.033 -1.258 4497 -0.035464
2010-02-19 -0.2082 1.022 -1.410 6327 -0.059933
2010-04-10  0.1315 0.995 -1.671 9541 -0.004637
attr(,"lat")
[1] 37.2
```

With the function fBTd it is possible to get time bases with different structures. Thus, the calculations for the so called "average days" need the next piece of code, with the result displayed in the figure 1.

```
> lat = 37.2
> SolD <- fSolD(lat, BTd = fBTd(mode = "prom"))
> SolI <- fSolI(SolD, sample = "10 min", keep.night = FALSE)
```

These calculations can also be carried out for the whole year (figure 2).

```
> BTd = fBTd(mode = "serie")
> solD <- fSolD(lat, BTd)
> summary(solD)

     Index                 decl                 eo               ws
 Min.   :2010-01-01   Min.   :-4.09e-01   Min.   :0.967   Min.   :-1.91
 1st Qu.:2010-04-02   1st Qu.:-2.89e-01   1st Qu.:0.977   1st Qu.:-1.80
 Median :2010-07-02   Median : 2.63e-16   Median :1.000   Median :-1.57
 Mean   :2010-07-02   Mean   : 9.31e-18   Mean   :1.000   Mean   :-1.57
 3rd Qu.:2010-10-01   3rd Qu.: 2.89e-01   3rd Qu.:1.023   3rd Qu.:-1.34
 Max.   :2010-12-31   Max.   : 4.09e-01   Max.   :1.033   Max.   :-1.24
      Bo0d            EoT
 Min.   : 4235   Min.   :-6.18e-02
 1st Qu.: 5472   1st Qu.:-2.59e-02
 Median : 8302   Median :-2.48e-03
 Mean   : 8116   Mean   : 1.24e-05
 3rd Qu.:10742   3rd Qu.: 2.16e-02
 Max.   :11607   Max.   : 7.09e-02
```

These two functions have been included in a new function, calcSol. This function constructs an object of class Sol containing in its slots the zoo objects created by fSolD and fSolI. This class owns methods for getting and displaying information (for example, as.zooD, as.zooI, xyplot).

3 Solar Radiation

Values of global horizontal irradiation are commonly available, either as monthly averages of daily values or as a time series of daily during one or several years. The analysis of the performance of a PV system starts from the transformation of the global horizontal irradiation to global, diffuse and direct horizontal irradiance and irradiation, and then irradiance and irradiation on the generator surface.

3.1 Irradiation and irradiance on the horizontal plane

The function fCompD extracts the diffuse and direct components from the daily global irradiation on a horizontal surface by means of regressions between the clearness index and the diffuse fraction parameters. This function need the results from fSolD, a set of values of global horizontal irradiation ($^{Wh}/_{m^2}$), and the correlation between the clearness index and the diffuse fraction. The current version of solaR includes the correlations proposed by Collares Pereira and Rabl [**?**], and Page [4]. Besides, the user may define a particular correlation through the argument f. Once again for a certain day:

```
> BTd = fBTd(mode = "serie")
> SolD <- fSolD(lat, BTd[100])
> SolI <- fSolI(SolD, sample = "hour")
> G0d = zoo(5000, index(SolD))
> fCompD(SolD, G0d, corr = "Page")

               Fd    Ktd  G0d  D0d  B0d
2010-04-10 0.4078 0.5241 5000 2039 2961

> fCompD(SolD, G0d, corr = "CPR")

               Fd    Ktd  G0d  D0d  B0d
2010-04-10 0.5582 0.5241 5000 2791 2209
```

and for the "average days":

```
> mon = month.abb
> p <- xyplot(AlS * 180/pi ~ AzS * 180/pi, groups = month, data = SolI,
+     type = "l", col = "black", xlab = expression(psi[s]), ylab = expression(gamma[s]))
> plab = p + glayer(panel.text(0, y[x == 0], mon[group.value],
+     pos = 4, cex = 0.8))
> print(plab)
```

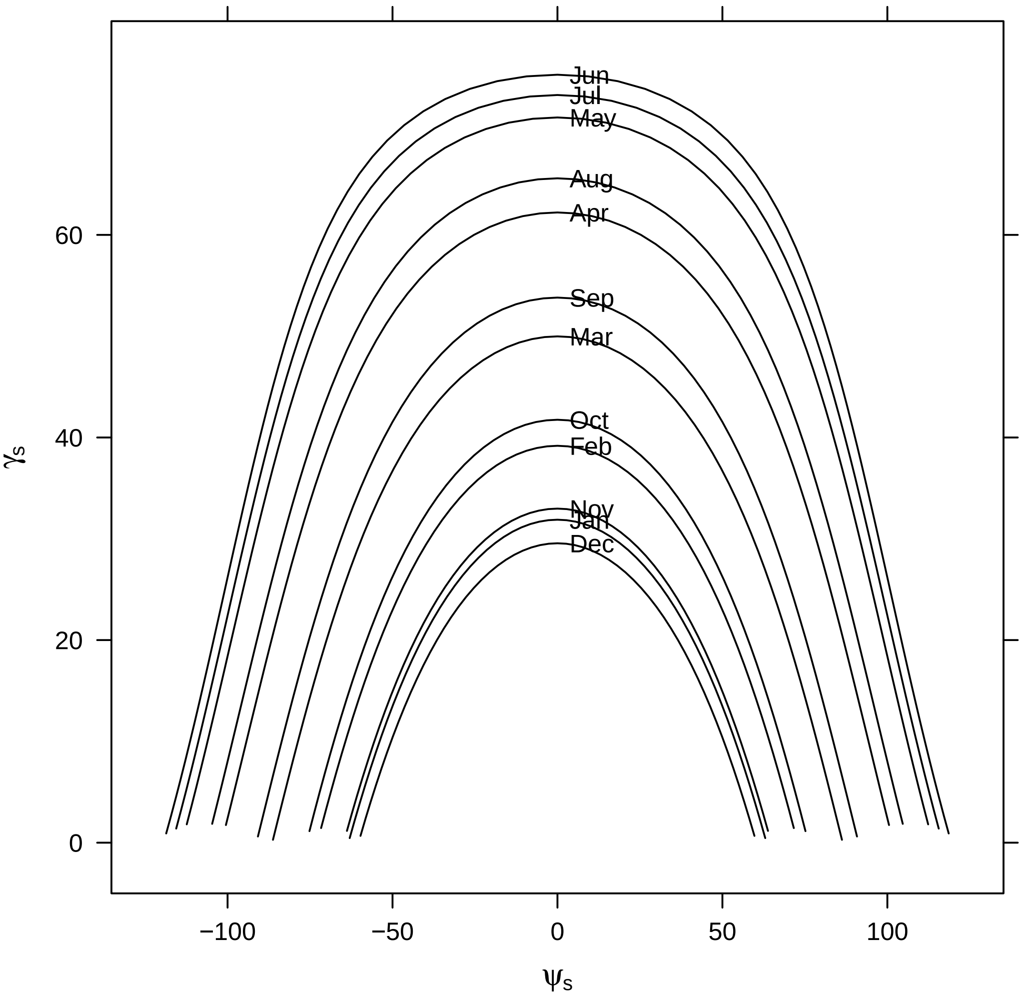

Figure 1: Azimuth and height solar angles during the “average days”.

```
> p <- xyplot(solD$decl)
> print(p)
```

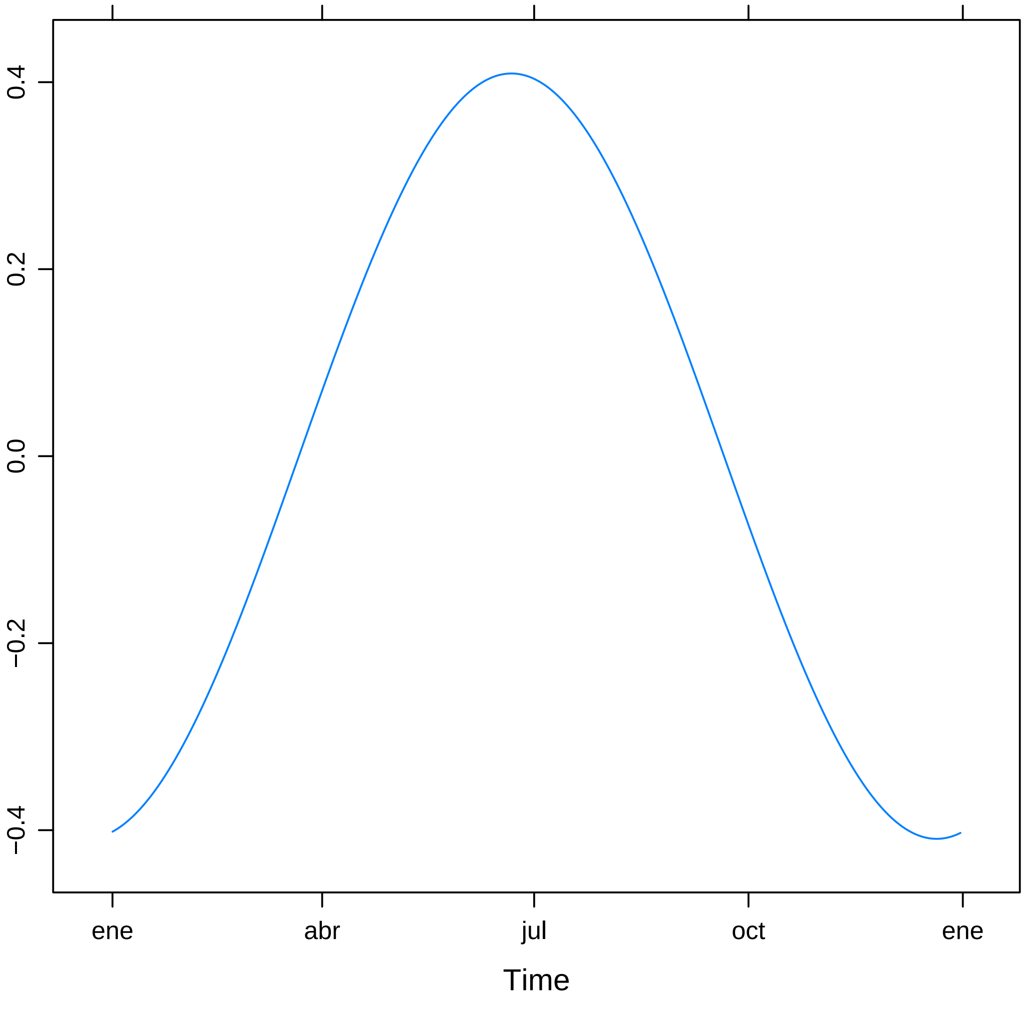

Figure 2: Declination throughout the year

```
> lat = 37.2
> G0dm = c(2.766, 3.491, 4.494, 5.912, 6.989, 7.742, 7.919, 7.027,
+     5.369, 3.562, 2.814, 2.179) * 1000
> Rad = readG0dm(G0dm, lat)
> solD <- fSolD(lat, fBTd(mode = "prom"))
> fCompD(solD, Rad, corr = "Page")

               Fd    Ktd  G0d    D0d  B0d
2010-01-17 0.3354 0.5882 2766  927.6 1838
2010-02-14 0.3452 0.5794 3491 1205.2 2286
2010-03-15 0.3573 0.5687 4494 1605.9 2888
2010-04-15 0.3195 0.6022 5912 1888.9 4023
2010-05-15 0.2871 0.6309 6989 2006.5 4982
2010-06-10 0.2437 0.6693 7742 1886.8 5855
2010-07-18 0.2070 0.7018 7919 1639.0 6280
2010-08-18 0.2209 0.6894 7027 1552.4 5475
2010-09-18 0.2804 0.6368 5369 1505.6 3863
2010-10-19 0.3728 0.5550 3562 1328.1 2234
2010-11-18 0.3475 0.5775 2814  977.8 1836
2010-12-13 0.4233 0.5104 2179  922.3 1257
```

Let's use `corr='user'` define a a function with the correlation of Page. Obviously, we shall obtain the same result as with `corr='Page'`.

```
> fKTd = function(x) {
+     (0.99 * (x <= 0.17)) + (x > 0.17) * (1.188 - 2.272 * x +
+         9.473 * x^2 - 21.856 * x^3 + 14.648 * x^4)
+ }
> fCompD(SolD, G0d, corr = "user", f = fKTd)

               Fd    Ktd  G0d  D0d  B0d
2010-04-10 0.5582 0.5241 5000 2791 2209
```

The daily profile of irradiance is obtained with the function `fCompI`. This function needs the information provided by `fCompD` and `fSolI` or `calcSol`. For example the profiles for the "average days" are obtained with the next code (fig. 3).

```
> lat = 37.2
> sol <- calcSol(lat, fBTd(mode = "prom"), sample = "hour", keep.night = FALSE)
> G0dm = c(2.766, 3.491, 4.494, 5.912, 6.989, 7.742, 7.919, 7.027,
+     5.369, 3.562, 2.814, 2.179) * 1000
> Ta = c(10, 14.1, 15.6, 17.2, 19.3, 21.2, 28.4, 29.9, 24.3, 18.2,
+     17.2, 15.2)
> BD <- readG0dm(G0dm = G0dm, Ta = Ta, lat = 37.2)
> compD <- fCompD(sol, BD, corr = "Page")
> compI <- fCompI(compD, sol)
> summary(compI)

     Index                           kt               G0
 Min.   :2010-01-17 08:00:00   Min.   :0.401   Min.   :  6.19
 1st Qu.:2010-04-15 10:15:00   1st Qu.:0.507   1st Qu.:187.39
 Median :2010-06-10 18:30:00   Median :0.587   Median :419.26
 Mean   :2010-06-29 18:25:21   Mean   :0.581   Mean   :424.39
 3rd Qu.:2010-09-18 11:45:00   3rd Qu.:0.646   3rd Qu.:624.50
 Max.   :2010-12-13 16:00:00   Max.   :0.765   Max.   :972.56
       D0               B0
 Min.   :  2.59   Min.   :  3.59
 1st Qu.: 78.42   1st Qu.:116.48
 Median :130.24   Median :265.97
 Mean   :122.86   Mean   :301.53
 3rd Qu.:170.43   3rd Qu.:453.84
 Max.   :230.50   Max.   :787.71
```

3.1.1 Meteorological data

The function `readMAPA` is able to download the meteorological data available at www.mapa.es/siar. This webpage provides daily measurements from a set of agroclimatic stations located in Spain. This function needs the code of the station and its province, and the start and end date. The codes of stations and provinces are stored at the dataset `RedEstaciones`. For example, there are several stations in Madrid:

```
> data(RedEstaciones)
> Madrid <- subset(RedEstaciones, NomProv == "Madrid")
> print(Madrid)

     Provincia Estacion NomProv                      NomEst
P209        28        1  Madrid Center:_Finca_experimental
P210        28        2  Madrid                     Arganda
P211        28        3  Madrid                    Aranjuez
P212        28        4  Madrid         Fuentiduena_de_Tajo
P213        28        5  Madrid        San_Martin_de_la_Vega
P214        28        6  Madrid                    Chinchon
P215        28      102  Madrid               Villa_del_Prado
```

```
> p <- xyplot(G0 + B0 + D0 ~ w | month, data = compI, type = "l",
+     auto.key = list(space = "right"))
> print(p)
```

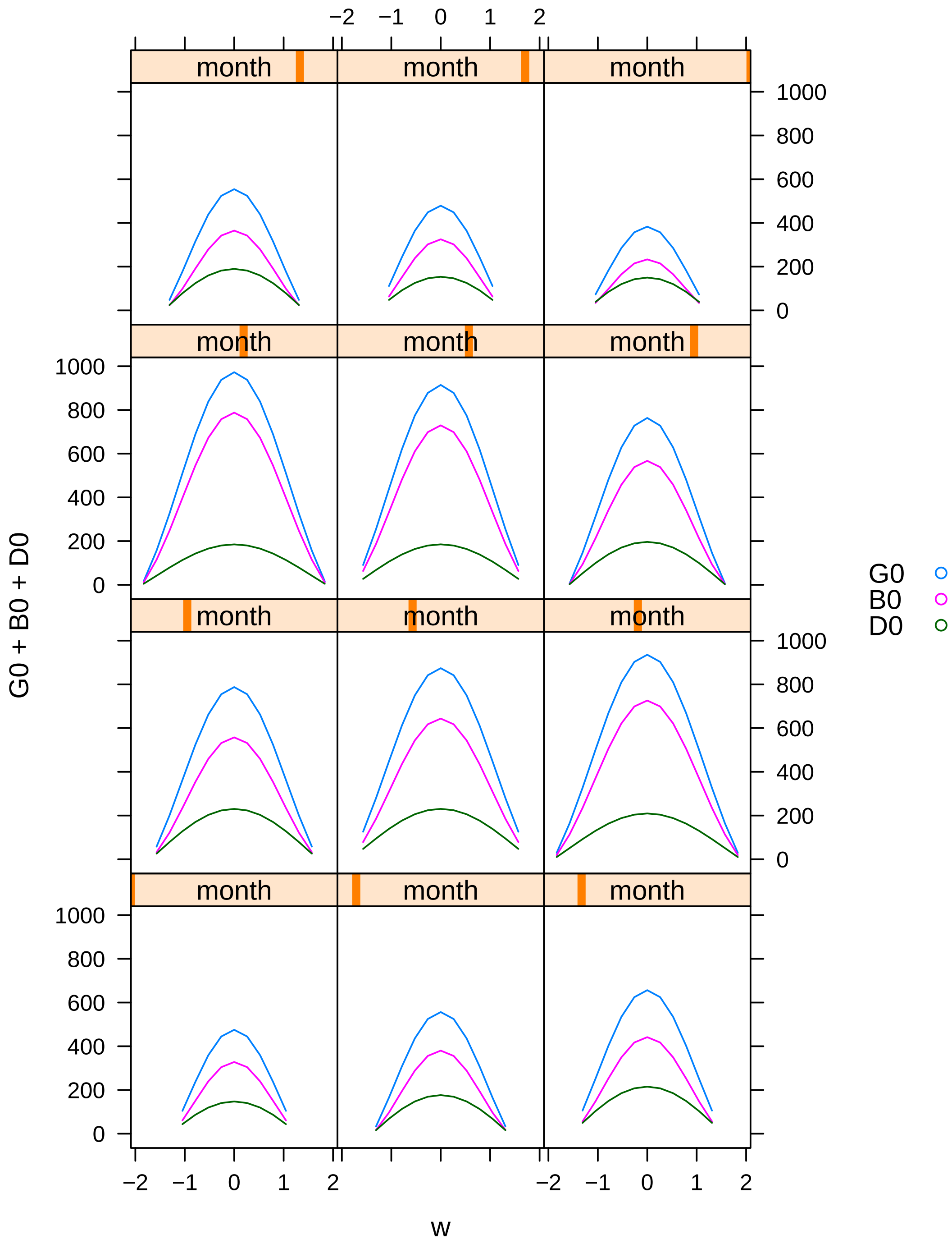

Figure 3: Global, diffuse, and direct irradiance during the "average days".

readMAPA constructs an object of class Meteo. The data is obtained with the method getData. If only the irradiation series is needed, the method getG0 is recommended.

For example, let's obtain the 2009 data from the station at Aranjuez (fig. 4). It is important to note that the radiation measurements available at the webpage are in $^{MJ}/_{m^2}$, but readMAPA converts the values to $^{Wh}/_{m^2}$:

```
> Aranjuez <- readMAPA(28, 3, "01/01/2009", "31/12/2009")

Downloading data from www.mapa.es/siar...

> print(Aranjuez)

Object of class  Meteo

Source of meteorological information: mapa-Est: 3 Prov: 28
Latitude of source:  0 degrees

Meteorological Data:
     Index                  TempMedia        TempMax       HorMinTempMax
 Min.    :2009-01-01   Min.    :-5.31   Min.    :-2.36   Min.    :   0
 1st Qu.:2009-04-02   1st Qu.: 8.85   1st Qu.:14.92   1st Qu.:1350
 Median :2009-07-02   Median :14.32   Median :23.72   Median :1440
 Mean   :2009-07-02   Mean   :15.33   Mean   :23.35   Mean   :1432
 3rd Qu.:2009-10-01   3rd Qu.:23.67   3rd Qu.:32.61   3rd Qu.:1520
 Max.   :2009-12-31   Max.   :30.68   Max.   :40.76   Max.   :2220

    TempMin       HorMinTempMin    HumedadMedia     HumedadMax      HorMinHumMax
 Min.   :-11.30   Min.   :   0   Min.   : 22.2   Min.   : 49.1   Min.   :   0
 1st Qu.:  2.07   1st Qu.: 440   1st Qu.: 42.4   1st Qu.: 79.1   1st Qu.: 420
 Median :  7.40   Median : 530   Median : 60.3   Median : 92.1   Median : 530
 Mean   :  7.48   Mean   : 711   Mean   : 59.8   Mean   : 96.7   Mean   : 679
 3rd Qu.: 13.26   3rd Qu.: 630   3rd Qu.: 74.7   3rd Qu.: 97.1   3rd Qu.: 640
 Max.   : 21.36   Max.   :2350   Max.   :100.0   Max.   :650.0   Max.   :2350

   HumedadMin      HorMinHumMin     VelViento        DirViento
 Min.   :   0.0   Min.   :   0   Min.   :  0.272   Min.   :  1.12
 1st Qu.:  14.3   1st Qu.:1400   1st Qu.:  0.754   1st Qu.: 43.89
 Median :  26.4   Median :1510   Median :  1.062   Median :108.90
 Mean   :  64.3   Mean   :1414   Mean   :  4.916   Mean   :144.07
 3rd Qu.:  47.8   3rd Qu.:1600   3rd Qu.:  1.778   3rd Qu.:239.80
 Max.   :1640.0   Max.   :2310   Max.   :359.600   Max.   :357.70

  VelVientoMax     DirVientoVelMax  HorMinVelMax   Precipitacion        EtPMon
 Min.   :  1.57   Min.   :   0   Min.   :    0   Min.   : 0.00   Min.   :0.00
 1st Qu.:  4.22   1st Qu.: 193   1st Qu.:1217   1st Qu.: 0.00   1st Qu.:1.38
 Median :  5.82   Median : 250   Median :1358   Median : 0.00   Median :2.88
 Mean   : 10.28   Mean   : 244   Mean   :1330   Mean   : 1.19   Mean   :3.41
 3rd Qu.:  7.66   3rd Qu.: 270   3rd Qu.:1523   3rd Qu.: 0.20   3rd Qu.:5.38
 Max.   :338.20   Max.   :1834   Max.   :2356   Max.   :24.83   Max.   :8.56
                                                                 NA's   :8.00
       G
 Min.   :  77
 1st Qu.:2639
 Median :5147
 Mean   :4845
 3rd Qu.:7169
 Max.   :8753
 NA's   :   8
```

This database includes information of maximum and minimum values of temperature. The function fTemp calculates a profile of the ambient temperature with this information following the method proposed in [2]. The evolution of this synthetic temperature during March is displayed in the figure 5.

```
> lat = 41
> sol = calcSol(lat, BTd = indexD(Aranjuez), sample = "hour")
> Temp <- fTemp(sol, Aranjuez)
```

There are more functions to construct a Meteo object with radiation and temperature data. If the data is stored in a local file or a data.frame, the functions readBD and df2Meteo are recommended, while readG0dm is indicated when only 12 monthly means are available.

3.1.2 The function calcG0

The previous steps are included in the function calcG0. For example, with the next code, the components of horizontal irradiation and irradiance are obtained from the measurements of the meteorological station of Aranjuez (figure 6).

```
> p = xyplot(G ~ TempMedia | month, data = Aranjuez, type = c("p",
+     "r"))
> print(p)
```

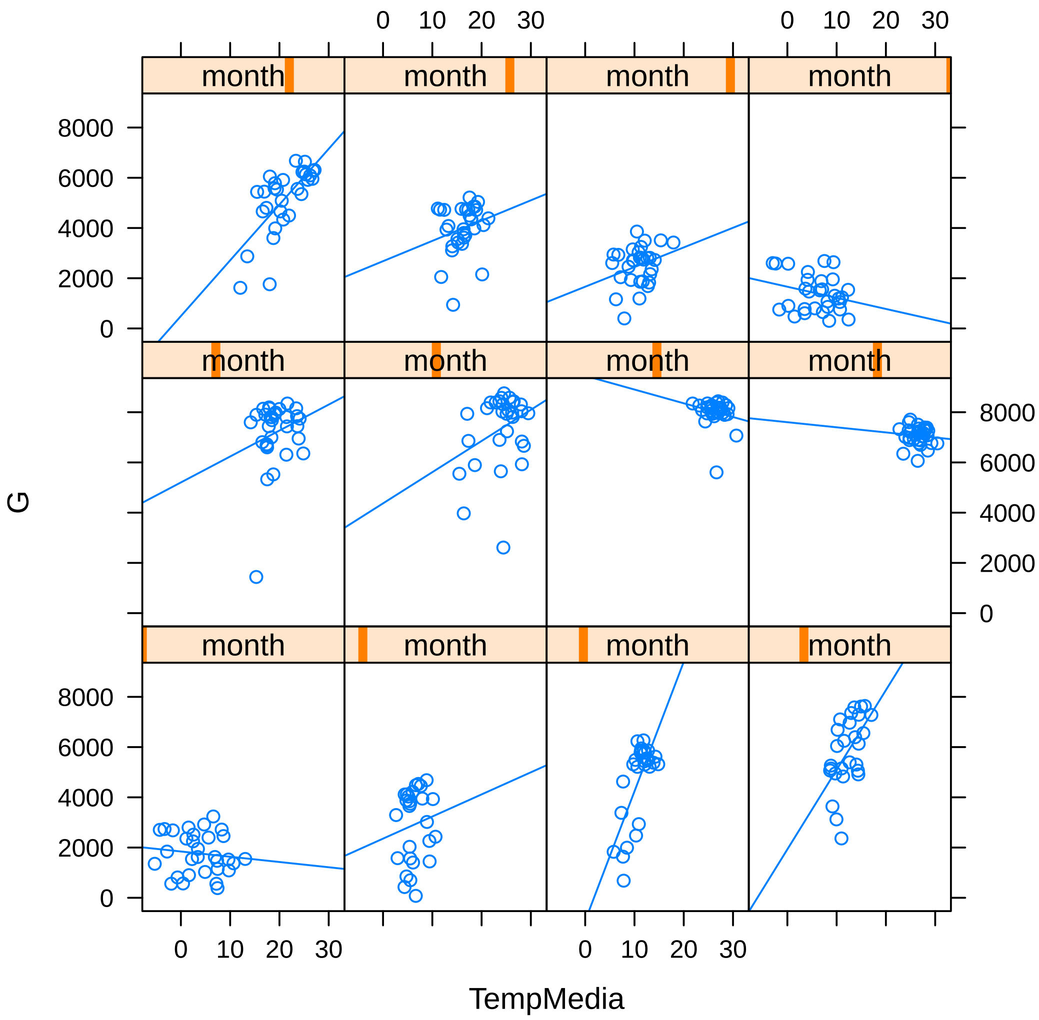

Figure 4: Daily irradiation and mean temperature in the station of Aranjuez.

```
> wTemp = window(Temp, start = as.POSIXct("2009-03-01"), end = as.POSIXct("2009-03-31"))
> p = xyplot(wTemp, col = "black", ylab = "T") + layer_(panel.xblocks(x,
+     DoY, col = c("lightgray", "white")))
> print(p)
```

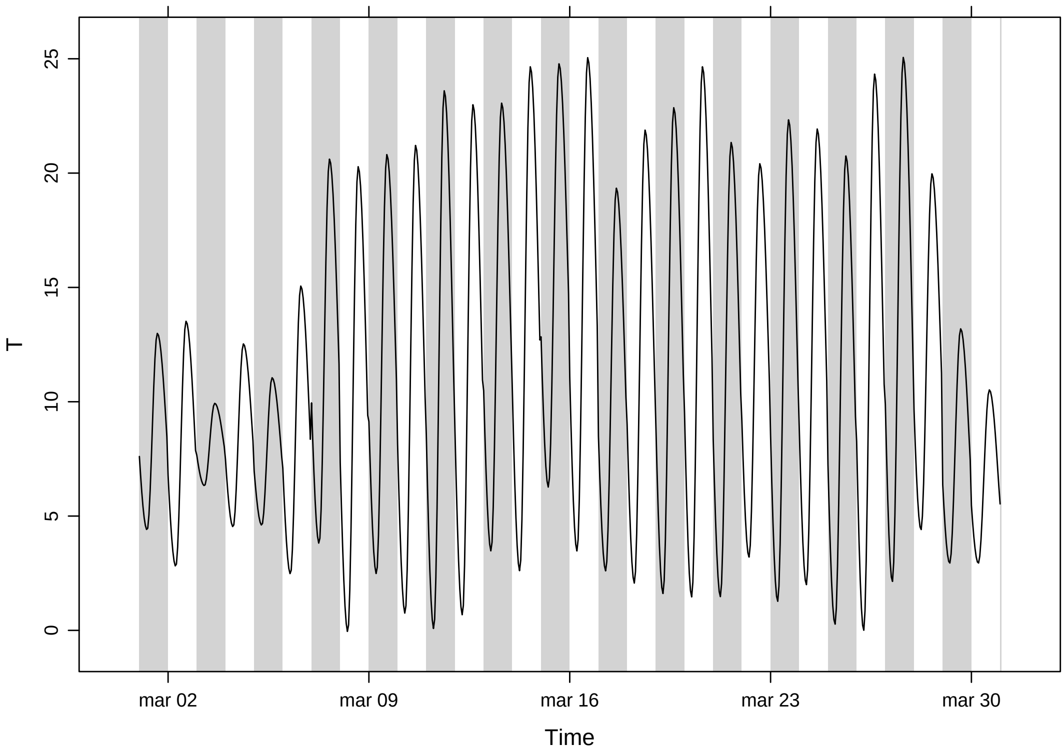

Figure 5: Evolution of the ambiente temperature during March 2009 in Aranjuez.

```
> g0 <- calcG0(lat = 37.2, modeRad = "mapa", mapa = list(prov = 28,
+     est = 3, start = "01/01/2009", end = "31/12/2009"))

Downloading data from www.mapa.es/siar...

> print(g0)

Object of class  G0

Source of meteorological information: mapa-Est: 3 Prov: 28

Latitude of source:  37.2 degrees
Latitude for calculations:  37.2 degrees

Monthly averages:
           G0d    D0d    B0d
ene 2009 1.764 1.1461 0.6176
feb 2009 2.916 1.2915 1.6244
mar 2009 4.725 1.5877 3.1371
abr 2009 5.819 2.2890 3.5303
may 2009 7.198 2.2475 4.9510
jun 2009 7.354 2.4525 4.9013
jul 2009 8.002 2.0457 5.9566
ago 2009 7.061 1.9446 5.1160
sep 2009 5.168 1.8897 3.2782
oct 2009 3.993 1.4684 2.5244
nov 2009 2.510 1.3175 1.1920
dic 2009 1.397 0.9773 0.4192

Yearly values:
      G0d   D0d  B0d
2009 1730 614.7 1115
```

3.2 Irradiation and irradiance on the generator plane

The solar irradiance incident on an inclined surface can be calculated from the direct and diffuse irradiance on a horizontal surface, and from the evolution of the angles of the Sun and the surface. The transformation of the direct radiation is straightforward since only geometric considerations are needed. However, the treatment of the diffuse irradiance is more complex since it involves the modelling of the atmosphere. There are several models for the estimation of diffuse irradiance on an inclined surface. The one which combines simplicity and acceptable results is the proposal of Hay and McKay. This model divides the diffuse component in isotropic and anisotropic whose values depends on a anisotropy index. On the other hand, the effective irradiance, the fraction of the incident irradiance that reaches the cells inside a PV module, is calculated with the losses due to the angle of incidence and dirtiness. This behaviour can be simulated with a model proposed by Martin and Ruiz requiring information about the angles of the surface and the level of dirtiness [3].

The orientation, azimuth and incidence angle are calculated from the results of `fSolI` or `calcSol` with the functions `fTheta` `fInclin`. These functions can calculate the movement and irradiance for fixed systems, and two-axis and horizontal N-S trackers. Besides, the the movement of a horizontal NS tracker due to the backtracking strategy [5] can be calculated with information about the tracker and the distance between the trackers included in the system.

Both functions are integrated in `calcGef`, which construct an object of class `Gef`. Once again, this class owns methods for obtaining and displaying information.

For example, with the previous results, we can calculate the irradiance and irradiation on a fixed surface. The figure 7 shows the relation between the effective and incident irradiance versus the cosine of the angle of incidence for this system.

```
> p = xyplot(g0)
> print(p)
```

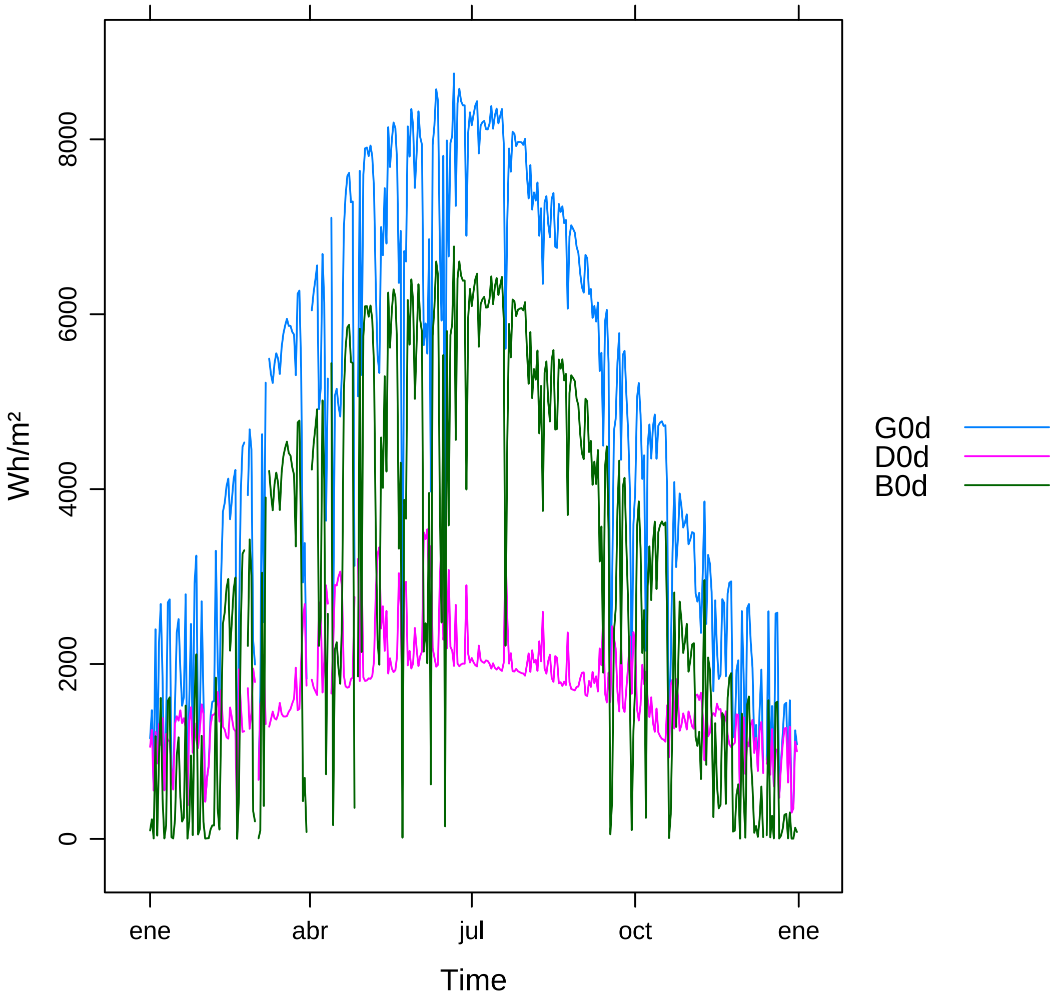

Figure 6: Components of horizontal irradiation calculated with `calcG0`.

```
> gef <- calcGef(lat = 37.2, modeRad = "prev", prev = g0, beta = 30)
> print(gef)

Object of class  Gef

Source of meteorological information: mapa-Est: 3 Prov: 28

Latitude of source:  37.2 degrees
Latitude for calculations:  37.2 degrees

Monthly averages:
            Bod  Gefd   Defd   Befd
ene 2009  8.720 2.202 1.1248 1.0600
feb 2009  9.801 3.590 1.2721 2.2907
mar 2009 10.289 4.933 1.4229 3.4693
abr 2009 10.428 5.194 1.8782 3.2654
may 2009 10.225 6.480 1.9645 4.4461
jun 2009 10.025 6.284 2.0870 4.1265
jul 2009 10.080 6.989 1.7606 5.1518
ago 2009 10.281 6.799 1.7726 4.9591
sep 2009 10.270 5.585 1.8129 3.7228
oct 2009  9.894 5.096 1.5445 3.5135
nov 2009  8.977 3.357 1.3684 1.9641
dic 2009  8.484 1.657 0.9117 0.7328

Yearly values:
      Bod Gefd  Defd Befd
2009 3573 1772 575.6 1180
-----------------
Mode of tracking:  fixed
    Inclination:  30
    Orientation:  0
```

The next lines of code calculate the movement of a N-S horizontal axis tracker with *backtracking* and whose inclination angle is limited to 60°. The evolution of the inclination angle is diplayed in the figure 8.

```
> G0dm = c(2766, 3491, 4494, 5912, 6989, 7742, 7919, 7027, 5369,
+     3562, 2814, 2179)
> Ta = c(10, 14.1, 15.6, 17.2, 19.3, 21.2, 28.4, 29.9, 24.3, 18.2,
+     17.2, 15.2)
> prom = list(G0dm = G0dm, Ta = Ta)
> structHoriz = list(L = 4.83)
> distHoriz = data.frame(Lew = structHoriz$L * 4, H = 0)
> gefBT = calcGef(lat = 37.2, prom = prom, sample = "10 min", modeTrk = "horiz",
+     modeShd = "bt", betaLim = 60, distances = distHoriz, struct = structHoriz)
```

4 Productivity of a Grid Connected PV System

From the previous irradiance calculations, the function `fProd` simulates the performance of a Grid Connected PV (GCPV) system paying attention to some parameters of the system (characteristics of the PV module and the inverter, the electrical arrangement of the PV generator, and the losses of the system).

For example, the electrical power, voltage and current of a certain PV system is calculated below.

```
> inclin = data.frame(Gef = c(200, 400, 600, 800, 1000), Ta = 25)
> fProd(inclin)

   Gef Ta    Tc   Voc   Isc  Vmpp   Impp   Vdc    Idc   Pac   Pdc   EffI
1  200 25 31.75 673.3 10.34 533.1  9.586 533.1  9.586  4212  4737 0.9164
2  400 25 38.50 655.4 20.68 516.3 19.090 516.3 19.090  8275  9137 0.9334
3  600 25 45.25 637.5 31.02 499.6 28.506 499.6 28.506 11972 13202 0.9346
4  800 25 52.00 619.7 41.36 483.0 37.824 483.0 37.824 15323 16936 0.9325
5 1000 25 58.75 601.8 51.70 466.5 47.037 466.5 47.037 18342 20342 0.9293
```

First, `fProd` computes the Maximum Power Point (MPP) of the generator (`Vmpp` and `Impp`) at the irradiance and ambient temperature conditions contained in `Inclin`. Next, it checks that this points is inside the MPP window of the inverter, as defined by `inverter$Vmin` and `inverter$Vmax`). If the MPP value is outside this range, the function asigns the limit value to the voltage, and calculates the correspondent current value with a warning. Anyway, the inverter input voltage and current are `Vdc` e `Idc`:

```
> inclin = data.frame(Gef = 800, Ta = 30)
> gen1 = list(Nms = 10, Nmp = 11)
> prod = fProd(inclin, generator = gen1)
> print(prod)

  Gef Ta Tc   Voc   Isc  Vmpp  Impp Vdc   Idc   Pac   Pdc   EffI
1 800 30 57 505.3 41.36 392.3 37.68 420 33.83 11943 13169 0.9346
```

For this configuration, the losses due to the voltage limitation are:

```
> p <- xyplot(Gef/G ~ cosTheta | month, data = gef, type = "smooth")
> print(p)
```

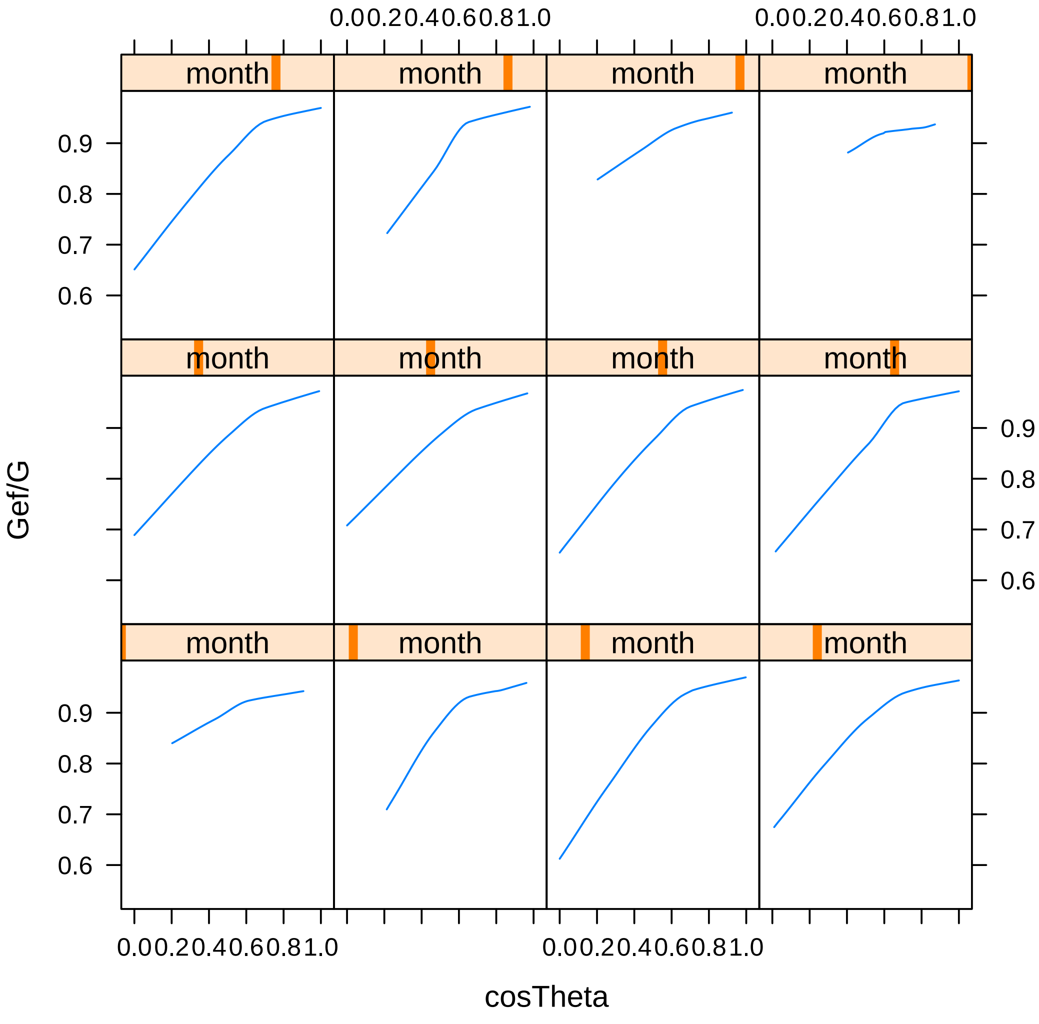

Figure 7: relation between the effective and incident irradiance versus the cosine of the angle of incidence for a fixed system.

```
> p <- xyplot(r2d(Beta) ~ r2d(w), data = gefBT, type = "l", xlab = expression(omega(degrees)),
+      ylab = expression(beta(degrees)))
> print(p)
```

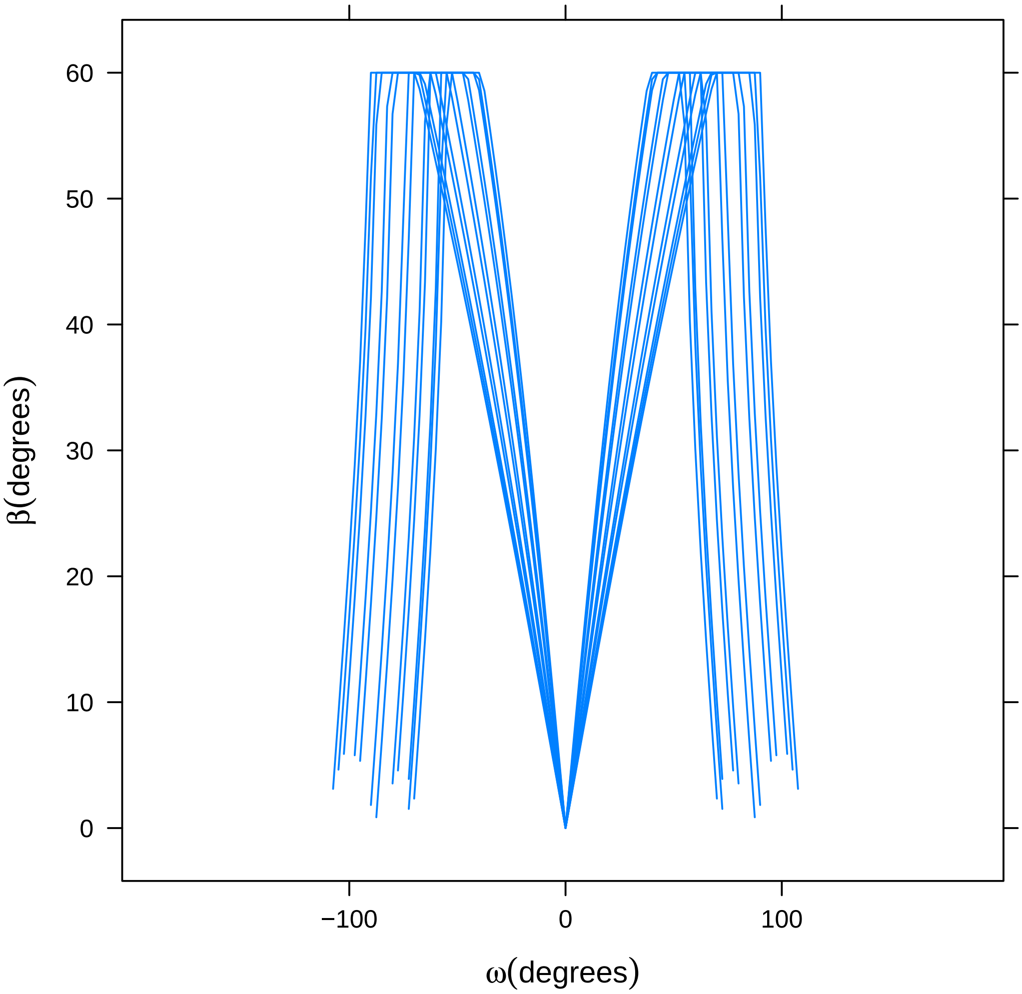

Figure 8: Evolution of the angle of inclination of a NS horizontal axis tracker with *backtracking* and limitation of angle.

```
> with(prod, Vdc * Idc/(Vmpp * Impp))

[1] 0.961
```

The function prodGCPV integrates the calculation procedure of irradiation, irradiance and simulation of the GCPV system. It constructs an object of class ProdGCPV.

The next code computes the productivity of the previous GCPV system working as fixed, NS horizontal axis tracking and two-axis tracking systems. The parameters of the generator, module, inverter and rest of the system are those by default in prodGCPV. The comparative of the performances is shown at the figure 9.

```
> lat = 37.2
> G0dm = c(2766, 3491, 4494, 5912, 6989, 7742, 7919, 7027, 5369,
+     3562, 2814, 2179)
> Ta = c(10, 14.1, 15.6, 17.2, 19.3, 21.2, 28.4, 29.9, 24.3, 18.2,
+     17.2, 15.2)
> prom = list(G0dm = G0dm, Ta = Ta)
> ProdFixed <- prodGCPV(lat = lat, prom = prom, keep.night = FALSE)
> Prod2x <- prodGCPV(lat = lat, prom = prom, modeTrk = "two", keep.night = FALSE)
> ProdHoriz <- prodGCPV(lat = lat, prom = prom, modeTrk = "horiz",
+     keep.night = FALSE)
```

4.1 Shadows

The shadows on PV generators alter the performance of the PV generators and reduce their productivity [6]. This package includes functions for the estimation of mutual shadows between generators from a same system. fSombra2X, fSombraHoriz, fSombraEst, calculate the shadows in two-axis, horizontal axis and fixed systems, respectively. The function fSombra6 is indicated for groups of 6 two-axis trackers. Finally, fSombra is a wrapper to the previous functions.

For example, the shadows factor of a tracker surrounded by five trackers is calculated in the next code box. The dimensions of the tracker structure and the configuration (rows and columns) of the plant are defined by struct, while the distances between the trackers are defined by distances. The figure 10 shows the evolution of the shadows factor during the day (X axis) and year (Y axis).

Since the data.frame distances does only have one row, the function fSombra6 builds a symmetric grid around the point (0,0,0), which is the affected tracker. This grid can also be constructed with:

```
> distances = data.frame(Lew = c(-40, 0, 40, -40, 40), Lns = c(30,
+     30, 30, 0, 0), H = 0)
> ShdFactor2 <- fSombra6(Angles, distances, struct, prom = FALSE)
> identical(coredata(ShdFactor), coredata(ShdFactor2))

[1] TRUE
```

Besides, distances can define a irregular grid around the affected tracker. Since this tracker is situated at (0,0,0), distances must have five rows. When prom=TRUE, fSombra6 provides a weighted averaged of the shadows in the whole set of trackers, whose distribution in the PV plant is defined by (Nrow y Ncol.

These functions are integrated in calcShd, calcGef and prodGCPV, as these examples show:

```
> struct2x = list(W = 23.11, L = 9.8, Nrow = 2, Ncol = 8)
> dist2x = data.frame(Lew = 40, Lns = 30, H = 0)
```

```
> ComparePac <- CBIND(two = as.zooI(Prod2x)$Pac, horiz = as.zooI(ProdHoriz)$Pac,
+     fixed = as.zooI(ProdFixed)$Pac)
> AngSol = as.zooI(as(ProdFixed, "Sol"))
> ComparePac = CBIND(AngSol, ComparePac)
> mon = month(index(ComparePac))
> p = xyplot(two + horiz + fixed ~ AzS | mon, data = ComparePac,
+     type = "l", auto.key = list(space = "right", lines = TRUE,
+         points = FALSE), ylab = "Pac")
> print(p)
```

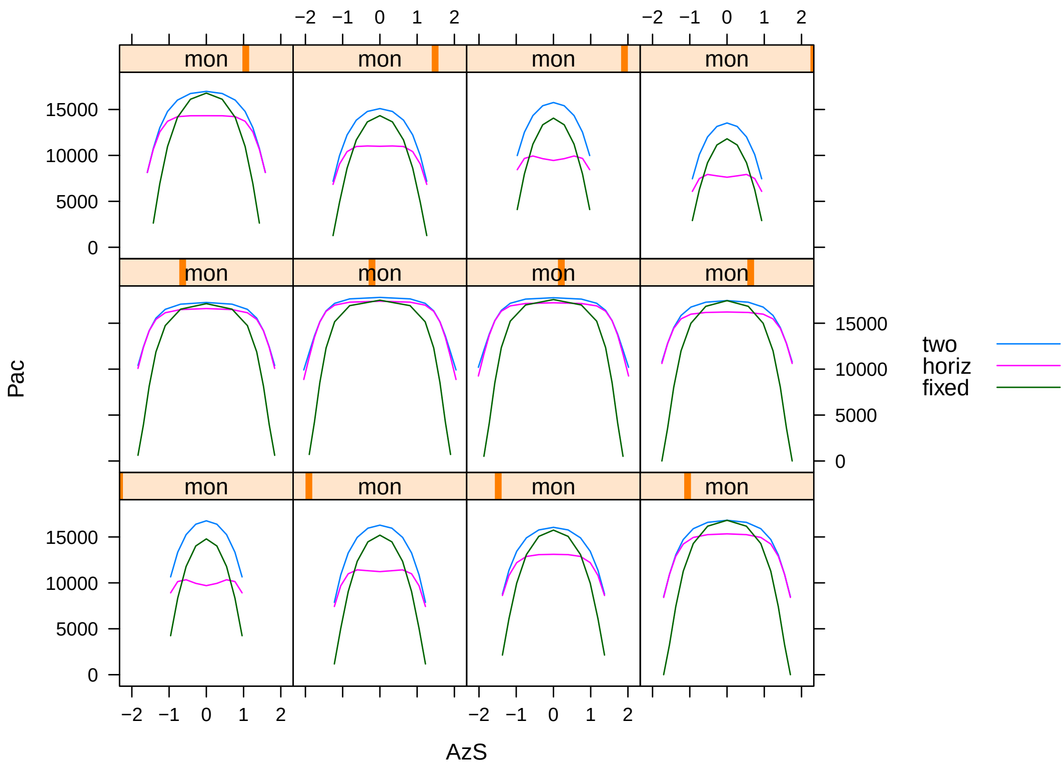

Figure 9: Comparative of performance between tracker strategies.

```
> YlOrBr = brewer.pal(n = 5, "YlOrBr")
> p <- levelplot(FS ~ w * day, data = Angles, col.regions = colorRampPalette(YlOrBr,
+     space = "Lab"))
> print(p)
```

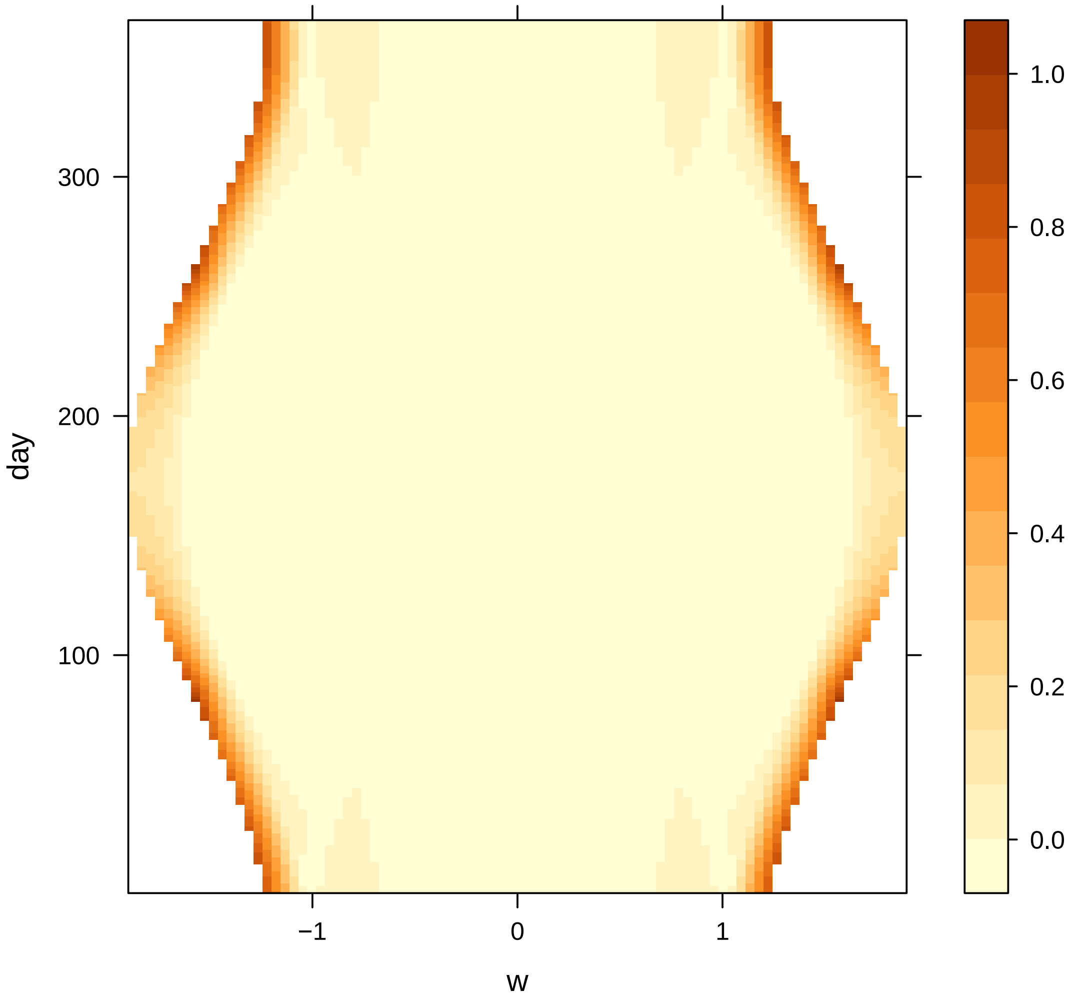

Figure 10: Shadows in a PV plant with two-axis trackers.

```
> prod2xShd <- prodGCPV(lat = lat, prom = prom, modeTrk = "two",
+     modeShd = "area", struct = struct2x, distances = dist2x)
> print(prod2xShd)

Object of class  ProdGCPV

Source of meteorological information: prom-

Latitude of source:  37.2 degrees
Latitude for calculations:  37.2 degrees

Monthly averages:
            Eac   Edc    Yf
ene 2010 123.70 136.7 4.675
feb 2010 132.75 146.9 5.017
mar 2010 141.32 156.1 5.341
abr 2010 168.73 186.6 6.377
may 2010 187.22 207.0 7.076
jun 2010 217.19 240.2 8.209
jul 2010 216.97 240.0 8.200
ago 2010 187.18 207.0 7.074
sep 2010 158.68 175.8 5.997
oct 2010 124.47 137.6 4.704
nov 2010 117.40 129.7 4.437
dic 2010  93.45 103.2 3.532

Yearly values:
       Eac   Edc   Yf
2010 56881 62895 2150
-----------------
Mode of tracking:  two
    Inclination limit: 90
-----------------
Generator:
    Modules in series:  12
    Modules in parallel:  11
    Nominal power (kWp):  26.5
```

```
> structHoriz = list(L = 4.83)
> distHoriz = data.frame(Lew = structHoriz$L * 4, H = 0)
> prodHorizShd <- prodGCPV(lat = lat, prom = prom, sample = "10 min",
+     modeTrk = "horiz", modeShd = "area", betaLim = 60, distances = distHoriz,
+     struct = structHoriz)
> print(prodHorizShd)

Object of class  ProdGCPV

Source of meteorological information: prom-

Latitude of source:  37.2 degrees
Latitude for calculations:  37.2 degrees

Monthly averages:
            Eac    Edc    Yf
ene 2010  84.51  93.37 3.194
feb 2010 101.34 111.95 3.830
mar 2010 124.15 137.13 4.692
abr 2010 158.60 175.33 5.994
may 2010 182.95 202.36 6.914
jun 2010 200.53 221.96 7.579
jul 2010 198.71 219.91 7.510
ago 2010 178.00 196.86 6.727
sep 2010 143.51 158.54 5.424
oct 2010  99.07 109.49 3.744
nov 2010  82.11  90.79 3.103
dic 2010  62.17  68.94 2.350

Yearly values:
       Eac   Edc   Yf
2010 49196 54403 1859
-----------------
Mode of tracking:  horiz
    Inclination limit: 60
-----------------
Generator:
    Modules in series:  12
    Modules in parallel:  11
    Nominal power (kWp):  26.5
```

```
> prodHorizBT <- prodGCPV(lat = lat, prom = prom, sample = "10 min",
+     modeTrk = "horiz", modeShd = "bt", betaLim = 60, distances = distHoriz,
+     struct = structHoriz)
> print(prodHorizBT)

Object of class  ProdGCPV

Source of meteorological information: prom-

Latitude of source:  37.2 degrees
Latitude for calculations:  37.2 degrees

Monthly averages:
            Eac    Edc    Yf
ene 2010  83.85  92.66 3.169
feb 2010 100.64 111.13 3.804
mar 2010 123.66 136.61 4.674
abr 2010 157.99 174.67 5.971
may 2010 182.22 201.58 6.887
jun 2010 199.60 220.88 7.544
jul 2010 197.73 218.86 7.473
ago 2010 177.14 195.94 6.695
sep 2010 142.87 157.86 5.400
oct 2010  98.54 108.85 3.724
nov 2010  81.42  89.98 3.077
dic 2010  61.77  68.51 2.335

Yearly values:
       Eac   Edc   Yf
2010 48946 54126 1850
-----------------
Mode of tracking:  horiz
    Inclination limit: 60
-----------------
Generator:
    Modules in series:  12
    Modules in parallel:  11
    Nominal power (kWp):  26.5
```

4.2 Position of trackers in a PV plant

The optimum distance between trackers or static structures of a PV grid connected plant depends on two main factors: the ground cover ratio (defined as the ratio of the PV array area to the total ground area), and the productivity of the system including shadow losses. Therefore, the optimum separation may be the one which achieves the highest productivity with the highest ground cover ratio. However, this definition is not complete since the terrain characteristics and the costs of wiring or civil works could alter the decision.

The function `optimShd` is a help for choosing this distance: it computes the productivity for a set of combinations of distances between the elements of the plant [6]. The designer should adopt the decision from these results with the adequate economical translations.

Let's analyse the configuration of a PV plant with NS horizontal axis trackers, without *backtracking*, and a height of 4,83 m. We are interested in a range of separations of 2 and 5 times this dimension. Besides, the analysis will be carried out with a limitation in the angle of inclination:

```
> structHoriz = list(L = 4.83)
> distHoriz = list(Lew = structHoriz$L * c(2, 5))
> Shd12Horiz <- optimShd(lat = lat, prom = prom, modeTrk = "horiz",
+     betaLim = 60, distances = distHoriz, res = 2, struct = structHoriz,
+     modeShd = "area", prog = FALSE)
> print(Shd12Horiz)

Object of class  Shade

Source of meteorological information: prom-

Latitude of source:  37.2 degrees
Latitude for calculations:  37.2 degrees

Dimensions of structure:
$L
[1] 4.83

Shade calculation mode:
[1] "area"
Productivity without shadows:
Object of class  ProdGCPV

Source of meteorological information: prom-

Latitude of source:  37.2 degrees
Latitude for calculations:  37.2 degrees

Monthly averages:
            Eac    Edc    Yf
ene 2010  87.48  96.48 3.306
feb 2010 110.99 122.45 4.195
mar 2010 127.37 140.51 4.814
abr 2010 166.91 184.33 6.308
may 2010 184.90 204.33 6.988
jun 2010 213.39 235.96 8.065
jul 2010 214.37 237.02 8.102
ago 2010 185.35 204.80 7.005
sep 2010 158.57 175.05 5.993
oct 2010 106.20 117.19 4.014
nov 2010  84.08  92.75 3.178
dic 2010  65.45  72.42 2.474

Yearly values:
       Eac   Edc   Yf
2010 51901 57326 1962
-----------------
Mode of tracking:  horiz
    Inclination limit: 60
-----------------
Generator:
    Modules in series:  12
    Modules in parallel:  11
    Nominal power (kWp):  26.5

Summary of results:
      Lew              H           FS               GCR              Yf
 Min.   : 9.66   Min.   :0   Min.   :0.0397   Min.   :2.00   Min.   :1714
 1st Qu.:13.16   1st Qu.:0   1st Qu.:0.0495   1st Qu.:2.72   1st Qu.:1793
 Median :16.66   Median :0   Median :0.0642   Median :3.45   Median :1836
 Mean   :16.66   Mean   :0   Mean   :0.0712   Mean   :3.45   Mean   :1822
 3rd Qu.:20.16   3rd Qu.:0   3rd Qu.:0.0859   3rd Qu.:4.17   3rd Qu.:1865
 Max.   :23.66   Max.   :0   Max.   :0.1261   Max.   :4.90   Max.   :1884
```

The function `optimShd` constructs an object of class `Shade` This class owns a S4 method of `plot` for displaying the results (figure 11).

Now, for a fixed system (figure 12):

```
> plot(Shd12Horiz)
```

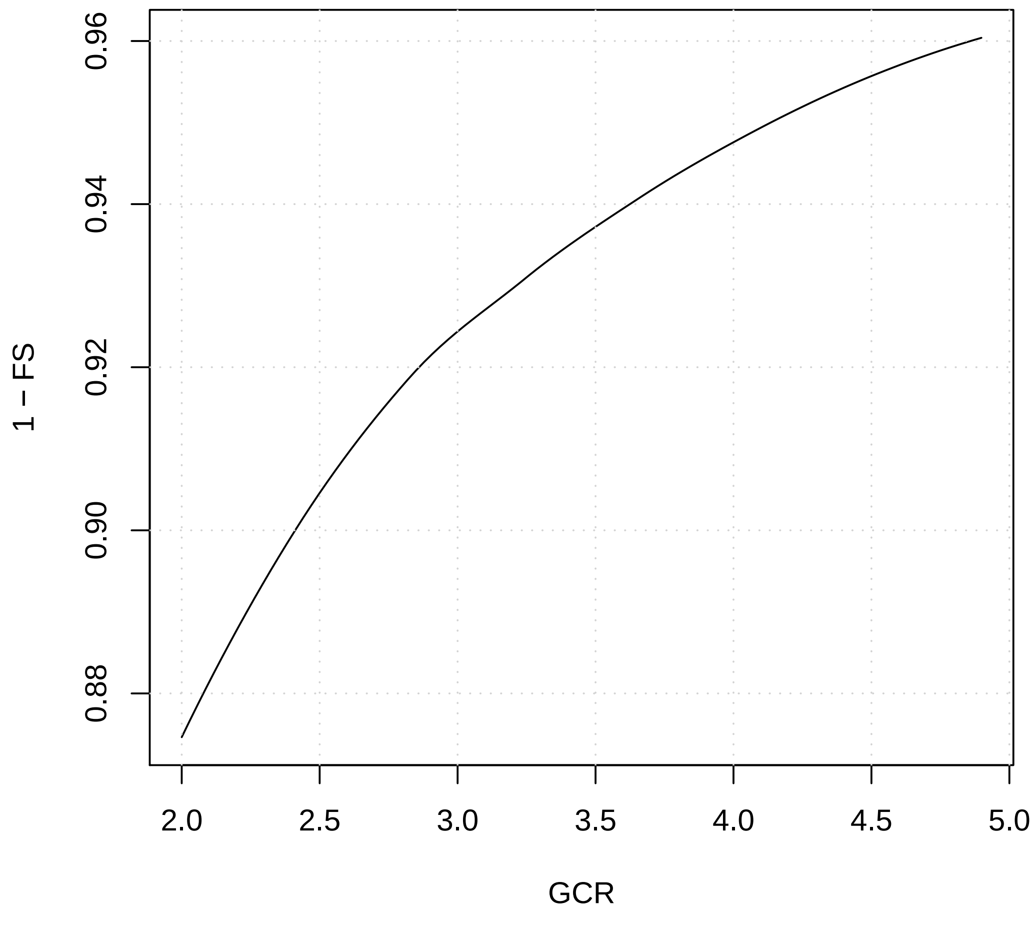

Figure 11: Mutual shadows in a NS horizontal axis tracking PV system.

```
> structFixed = list(L = 5)
> distFixed = list(D = structFixed$L * c(1, 3))
> Shd12Fixed <- optimShd(lat = lat, prom = prom, modeTrk = "fixed",
+     distances = distFixed, res = 1, struct = structFixed, modeShd = "area",
+     prog = FALSE)
> print(Shd12Fixed)

Object of class  Shade

Source of meteorological information: prom-

Latitude of source:  37.2 degrees
Latitude for calculations:  37.2 degrees

Dimensions of structure:
$L
[1] 5

Shade calculation mode:
[1] "area"
Productivity without shadows:
Object of class  ProdGCPV

Source of meteorological information: prom-

Latitude of source:  37.2 degrees
Latitude for calculations:  37.2 degrees

Monthly averages:
            Eac    Edc    Yf
ene 2010  91.56 101.24 3.460
feb 2010  99.34 110.18 3.755
mar 2010 108.42 120.10 4.098
abr 2010 121.63 134.64 4.597
may 2010 128.84 143.01 4.869
jun 2010 133.28 147.92 5.037
jul 2010 132.94 147.58 5.024
ago 2010 128.31 142.04 4.849
sep 2010 118.32 131.04 4.472
oct 2010  94.52 104.83 3.572
nov 2010  87.33  96.56 3.301
dic 2010  70.84  78.47 2.677

Yearly values:
       Eac   Edc   Yf
2010 40017 44345 1512
-----------------
Mode of tracking:  fixed
    Inclination:  27.2
    Orientation:  0
-----------------
Generator:
    Modules in series:  12
    Modules in parallel:  11
    Nominal power (kWp):  26.5

Summary of results:
       D              H           FS                 GCR            Yf
 Min.   : 5.0   Min.   :0   Min.   :0.000113   Min.   :1.0   Min.   :1319
 1st Qu.: 7.5   1st Qu.:0   1st Qu.:0.000749   1st Qu.:1.5   1st Qu.:1477
 Median :10.0   Median :0   Median :0.002811   Median :2.0   Median :1508
 Mean   :10.0   Mean   :0   Mean   :0.023061   Mean   :2.0   Mean   :1478
 3rd Qu.:12.5   3rd Qu.:0   3rd Qu.:0.023409   3rd Qu.:2.5   3rd Qu.:1511
 Max.   :15.0   Max.   :0   Max.   :0.127777   Max.   :3.0   Max.   :1512
```

Last, we are interested in a two-axis tracker 23,11 m width and 9,8 m height. We will try to design a PV plant with a grid of 2 rows and 8 columns.

```
> struct2x = list(W = 23.11, L = 9.8, Nrow = 2, Ncol = 8)
```

We will try the separations between 30 m and 50 m for the E-O direction and between 20 m and 50 m for the N-S direction.

```
> dist2x = list(Lew = c(30, 50), Lns = c(20, 50))
```

The results are obtained with a resolution of 5 m (figure 13):

```
> plot(Shd12Fixed)
```

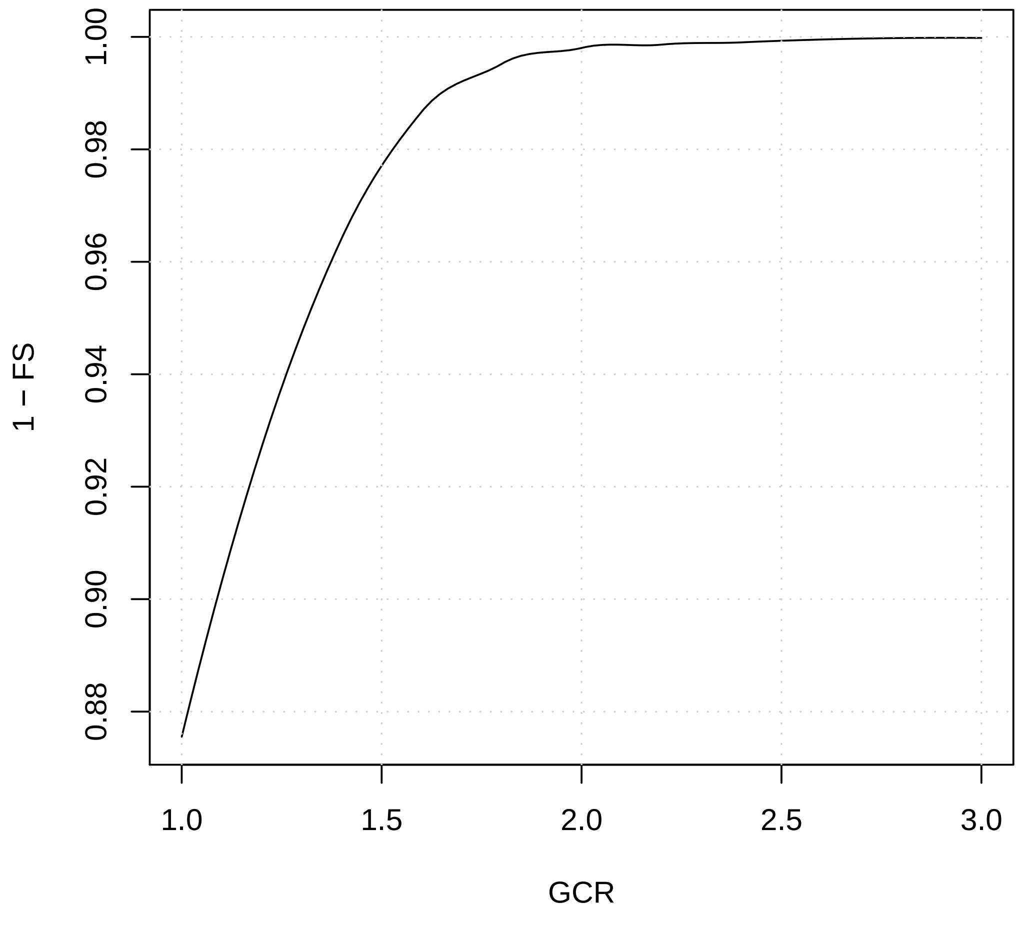

Figure 12: Mutual shadows in a PV plant with fixed structures.

```
> ShdM2x <- optimShd(lat = lat, prom = prom, modeTrk = "two", modeShd = c("area",
+     "prom"), distances = dist2x, struct = struct2x, res = 5,
+     prog = FALSE)
> print(ShdM2x)

Object of class  Shade

Source of meteorological information: prom-

Latitude of source:  37.2 degrees
Latitude for calculations:  37.2 degrees

Dimensions of structure:
$W
[1] 23.11

$L
[1] 9.8

$Nrow
[1] 2

$Ncol
[1] 8

Shade calculation mode:
[1] "area" "prom"
Productivity without shadows:
Object of class  ProdGCPV

Source of meteorological information: prom-

Latitude of source:  37.2 degrees
Latitude for calculations:  37.2 degrees

Monthly averages:
            Eac   Edc    Yf
ene 2010 128.01 141.4 4.838
feb 2010 142.11 157.0 5.371
mar 2010 144.55 159.6 5.463
abr 2010 176.14 194.6 6.657
may 2010 189.53 209.5 7.163
jun 2010 221.17 244.6 8.359
jul 2010 222.88 246.4 8.423
ago 2010 193.42 213.8 7.310
sep 2010 175.88 194.4 6.647
oct 2010 131.09 144.7 4.955
nov 2010 120.25 132.8 4.545
dic 2010  98.94 109.2 3.740

Yearly values:
       Eac   Edc   Yf
2010 59144 65355 2235
-----------------
Mode of tracking:  two
    Inclination limit: 90
-----------------
Generator:
    Modules in series:  12
    Modules in parallel:  11
    Nominal power (kWp):  26.5

Summary of results:
      Lew          Lns           H           FS              GCR
 Min.   :30   Min.   :20   Min.   :0   Min.   :0.0147   Min.   : 2.65
 1st Qu.:35   1st Qu.:25   1st Qu.:0   1st Qu.:0.0215   1st Qu.: 4.53
 Median :40   Median :35   Median :0   Median :0.0336   Median : 5.96
 Mean   :40   Mean   :35   Mean   :0   Mean   :0.0359   Mean   : 6.18
 3rd Qu.:45   3rd Qu.:45   3rd Qu.:0   3rd Qu.:0.0457   3rd Qu.: 7.73
 Max.   :50   Max.   :50   Max.   :0   Max.   :0.0913   Max.   :11.04
       Yf
 Min.   :2031
 1st Qu.:2133
 Median :2160
 Mean   :2155
 3rd Qu.:2187
 Max.   :2203
```

5 PV pumping systems

5.1 Simulation of centrifugal pumps

The first step for the simulation of the performance of a PV pumping system (PVPS) is the characterization of the pump under the supposition of constant manometric height [1]. With the function `fPump` compute the performance of the different parts of a centrifugal pump fed by a frequency converter following the affinity laws.

```
> plot(ShdM2x)
```

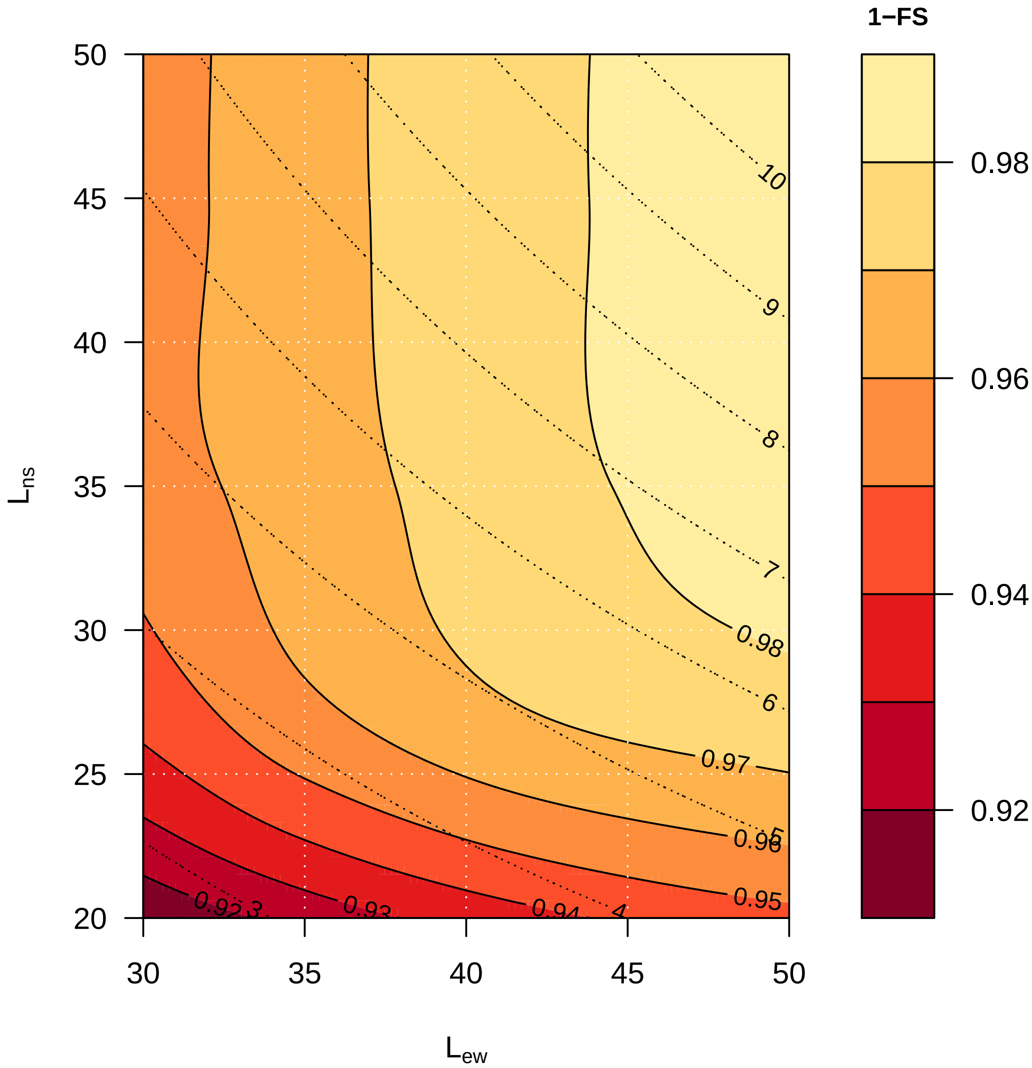

Figure 13: Mutual shadows in a two-axis tracking PV system for a combination of separations between trackers.

For example, with the function `fPump` we can characterize the performance of the SP8A44 pump (http://net.grundfos.com/Appl/WebCAPS/InitCtrl?mode=1) working with $H = 40\,\mathrm{m}$. The information of this pump is stored in the dataset `pumpCoef`.

```
> data(pumpCoef)
> CoefSP8A44 <- subset(pumpCoef, Qn == 8 & stages == 44)
> fSP8A44 <- fPump(pump = CoefSP8A44, H = 40)
```

The result of `fPump` is a set of functions which relate the electrical power and the flow, hydraulical and mechanical power, and frequency. These functions allow the calculation of the performance for any electrical power inside the range of the pump (figures 14 and 15):

```
> SP8A44 = with(fSP8A44, {
+     Pac = seq(lim[1], lim[2], by = 100)
+     Pb = fPb(Pac)
+     etam = Pb/Pac
+     Ph = fPh(Pac)
+     etab = Ph/Pb
+     f = fFreq(Pac)
+     Q = fQ(Pac)
+     result = data.frame(Q, Pac, Pb, Ph, etam, etab, f)
+ })
> SP8A44$etamb = with(SP8A44, etab * etam)
```

5.2 Nomograms of PVPS

The international standard IEC 61725 is of common usage in public licitations of PVPS. This standard proposes a equation of the irradiance profile with several parameters such as the length of the day, the daily irradiation and the maximum value of the irradiance. With this profile, the performance of a PVPS can be calculated for several manometric heights and nominal PV power values. A nomogram can display the set of combinations. This graphical tool can help to choose the best combination of pump and PV generator for certain conditions of irradiation and height Abella.Lorenzo.ea2003.

This kind of graphics are provided by the function `NmgPVPS`. For example, the 16) is a nomogram for the SP8A44 pump working in a range of heights from 50 to 80 meters, with a different PV generators. The peculiar shape of the curve of 50 meters shows that this pump does not work correctly with this height.

5.3 Productivity of PVPS

A different approach is to simulate the performance of the PVPS following the same procedure as the one described for the GCPV systems. The function `prodPVPS` is the equivalent to the function `prodSFCR`. The inputs are very similar between them, although there are some changes due to the different composition of the system. This function does not allow the calculation of shadows.

Once again with the SP8A44 pump, we compute the flow to be provided by this pump with a PV generator of 5500 Wp and a manometric height of 50 meters. The relation between flow and effective irradiance is displayed in the figure 17.

```
> lab = c(expression(eta[motor]), expression(eta[pump]), expression(eta[mp]))
> p <- xyplot(etam + etab + etamb ~ Pac, data = SP8A44, type = "l",
+     ylab = "Eficiencia")
> print(p + glayer(panel.text(x[1], y[1], lab[group.number], pos = 3)))
```

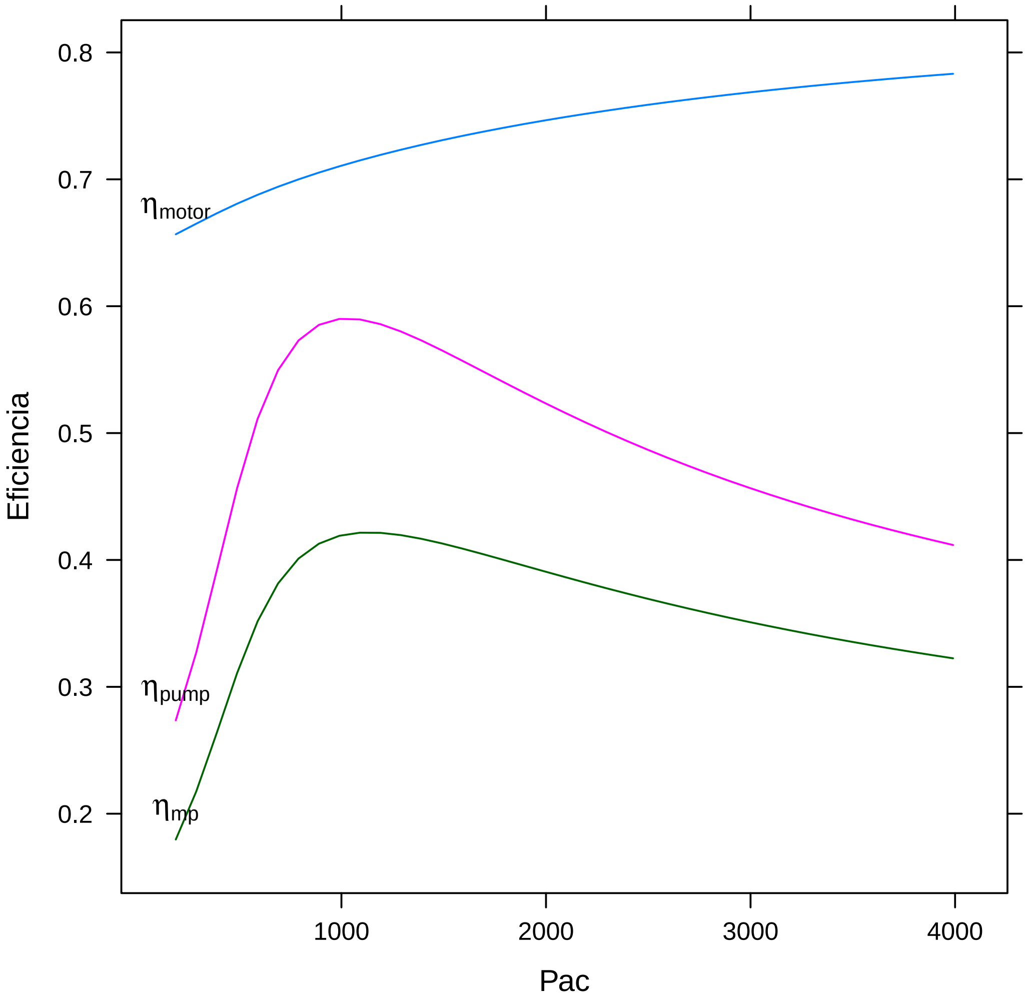

Figure 14: Efficiency of the motor and pump for several values of electrical power of a SP8A44 pump with $H = 40\,\mathrm{m}$

```
> lab = c(expression(P[pump]), expression(P[hyd]))
> p <- xyplot(Pb + Ph ~ Pac, data = SP8A44, type = "l", ylab = "Power (W)",
+     xlab = "AC power (W)")
> print(p + glayer(panel.text(x[length(x)], y[length(x)], lab[group.number],
+     pos = 3)))
```

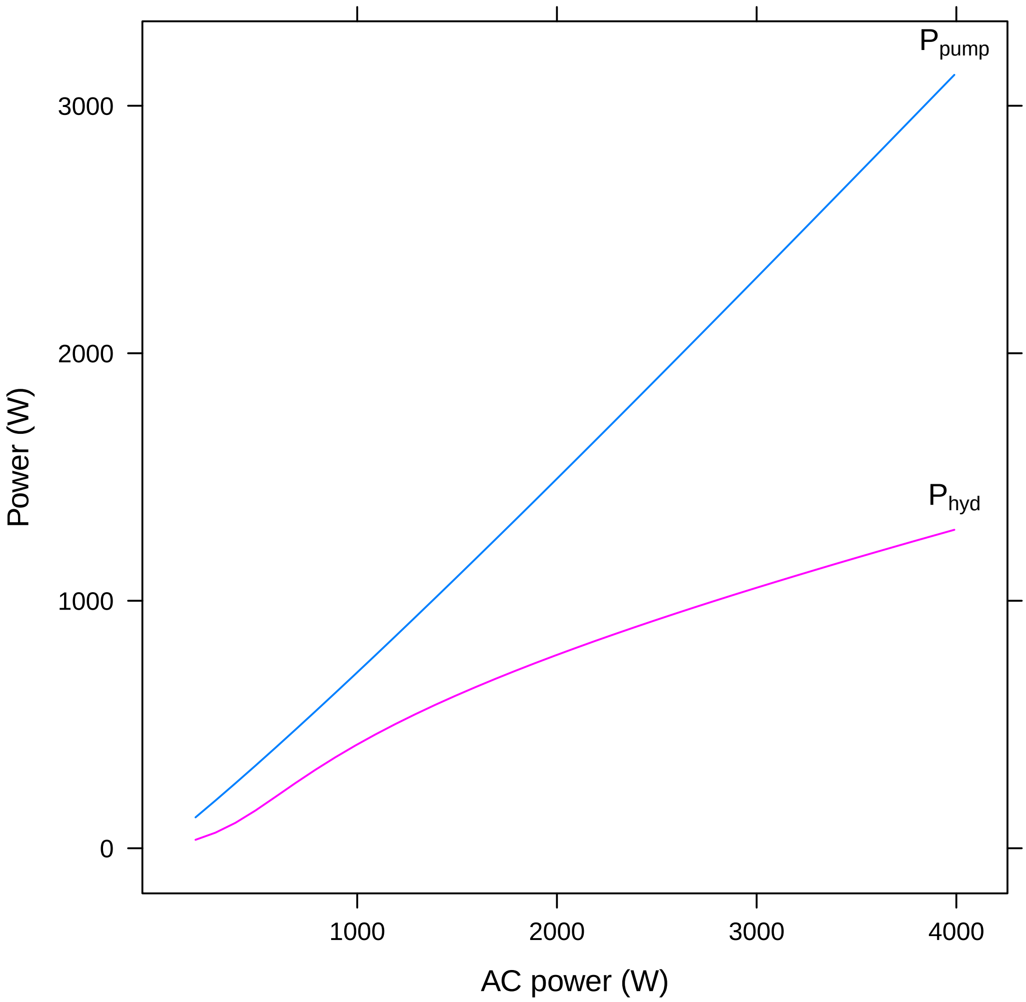

Figure 15: Mechanical and hydraulical power versus electrical power of a SP8A44 pump with $H = 40\,\mathrm{m}$.

```
> Pg = seq(3000, 5500, by = 500)
> H = seq(50, 80, by = 5)
> NmgSP8A44 <- NmgPVPS(pump = CoefSP8A44, Pg = Pg, H = H, Gd = 6000,
+     title = "Selection of Pumps", theme = custom.theme())
> print(NmgSP8A44$plot)
```

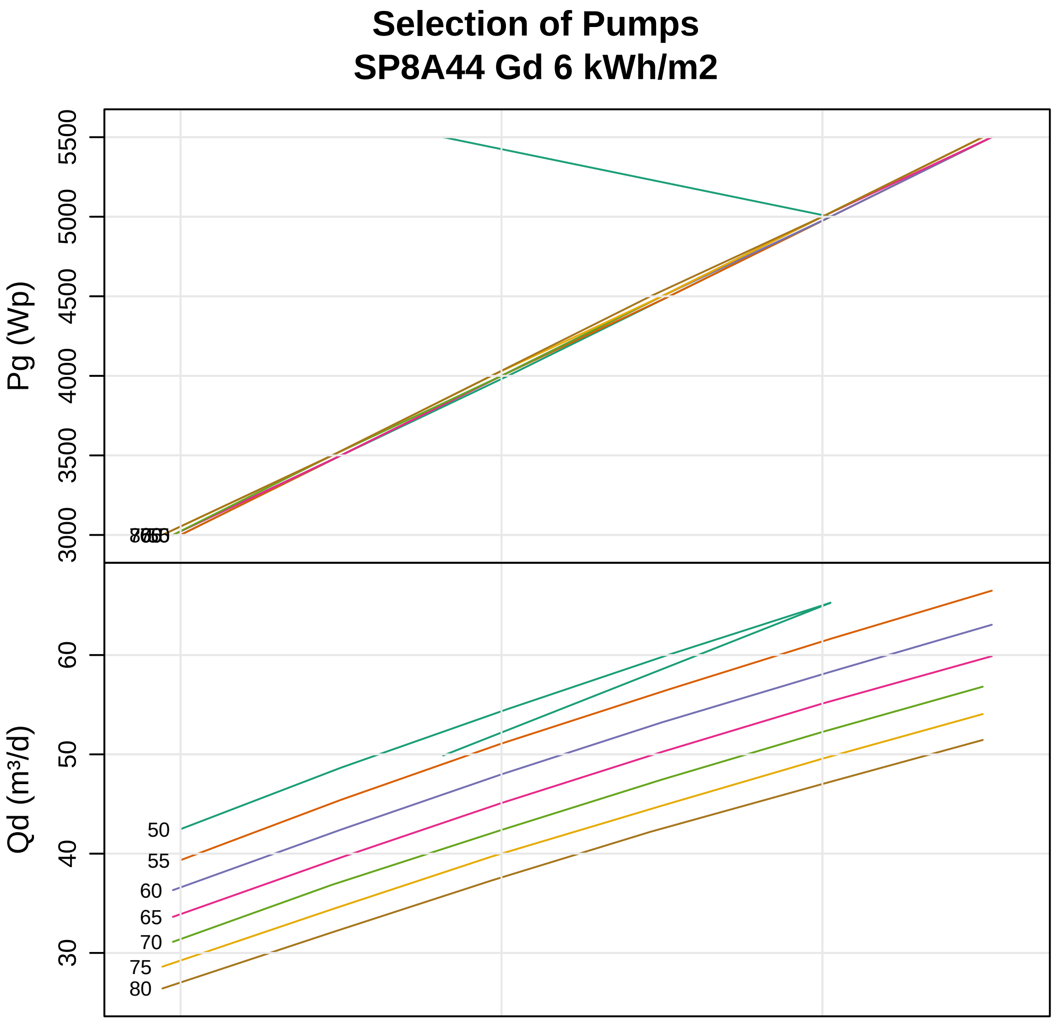

Figure 16: Nomogram for the SP8A44 pump working in a range of heights from 50 to 80 meters, with a different PV generators.

```
> prodSP8A44 <- prodPVPS(lat = 41, modeRad = "mapa", mapa = list(prov = 28,
+     est = 3, start = "01/01/2009", end = "31/12/2009"), pump = CoefSP8A44,
+     Pg = 5500, H = 50)

Downloading data from www.mapa.es/siar...

> print(prodSP8A44)

Object of class  ProdPVPS

Source of meteorological information: mapa-Est: 3 Prov: 28

Latitude of source:  41 degrees
Latitude for calculations:  41 degrees

Monthly averages:
            Eac    Qd    Yf
ene 2009 12.212 35.09 2.220
feb 2009 17.926 50.08 3.259
mar 2009 22.717 62.88 4.130
abr 2009 23.470 66.52 4.267
may 2009 27.700 78.55 5.036
jun 2009 26.231 75.39 4.769
jul 2009 28.641 81.38 5.207
ago 2009 28.180 79.82 5.124
sep 2009 24.587 69.68 4.470
oct 2009 23.877 67.31 4.341
nov 2009 17.578 50.85 3.196
dic 2009  9.146 25.89 1.663

Yearly values:
      Eac    Qd   Yf
2009 7985 22634 1452
-----------------
Mode of tracking:  fixed
    Inclination:  31
    Orientation:  0
-----------------
Pump:
    Qn:  8
    Stages:  44
Height (m):  50
Generator (Wp):  5500
```

Let's try to obtain more water with this pump using a larger PV generator of 7000 Wp. However, we can check that this is not a correct decision. Both the productivity and the water flow have decreased. The figure 18 shows that during the central months of the year, during the maximum irradiance periods, the pump reaches its limits of flow and frequency, and so the frequency converter stops the system.

```
> prodSP8A44Lim <- prodPVPS(lat, modeRad = "prev", prev = prodSP8A44,
+     pump = CoefSP8A44, H = 50, Pg = 7000)
```

6 Statistical analysis of PV plants

In a PV plant, the individual systems are theoretically identical and their performance along the time should be the same. Due to their practical differences –power tolerance, dispersion losses, dust–, the individual performance of each system will deviate from the average behaviour. However, when a system is performing correctly, these deviations are constrained inside a range and should not be regarded as sign of malfunctioning.

If these common deviations are assumed as a random process, a statistical analysis of the performance of the whole set of systems can identify a faulty system as the one that departs significantly from the mean behaviour.

The functions `analyzeData` and `TargetDiagram` compare the daily performance of each system with a reference (for example, the median of the whole set) during a time period of N days preceding the current day. They calculate a set of statistics of the performance of the PV plant as a whole, and another set of the comparison with the reference. This statistical analysis can be summarised with a graphical tool named "Target Diagram", which plots together the root mean square difference, the average difference and the standard deviation of the difference. Besides, this diagram includes the sign of the difference of the standard deviations of the system and the reference [7].

The next example uses a dataset of productivity from a PV plant composed of 22 systems (`data(prodEx)`). It is clear that the system no.22 is not working correctly during these periods (figure 20).

```
> data(prodEx)
> prodStat <- analyzeData(prodEx)
```

```
> p = xyplot(Q ~ Gef | month, data = prodSP8A44, cex = 0.5, type = c("p",
+     "smooth"), col.symbol = "gray", col.line = "black")
> print(p)
```

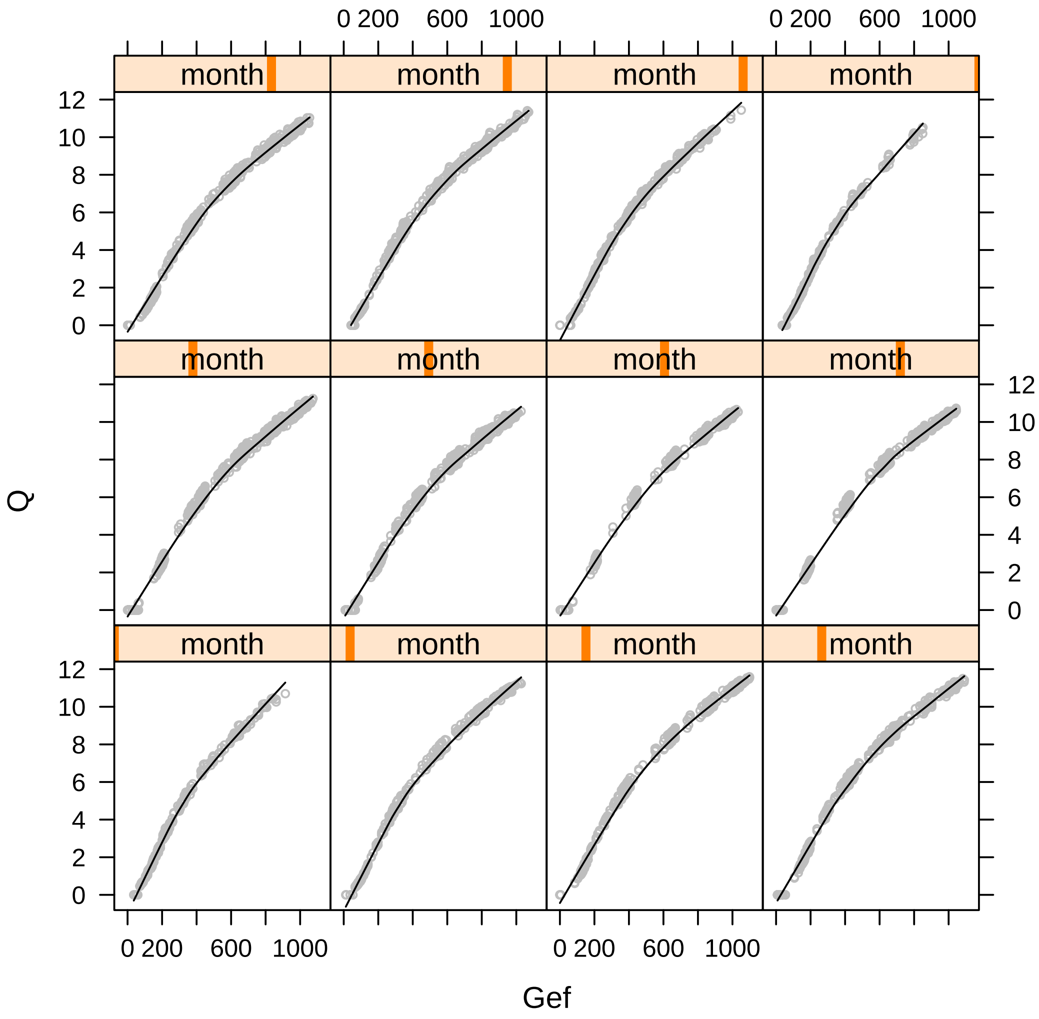

Figure 17: Flow versus irradiance of a PVPS with a SP8A44 pump and a PV generator with a nominal power of 5500 Wp and a manometric height of 50 meters.

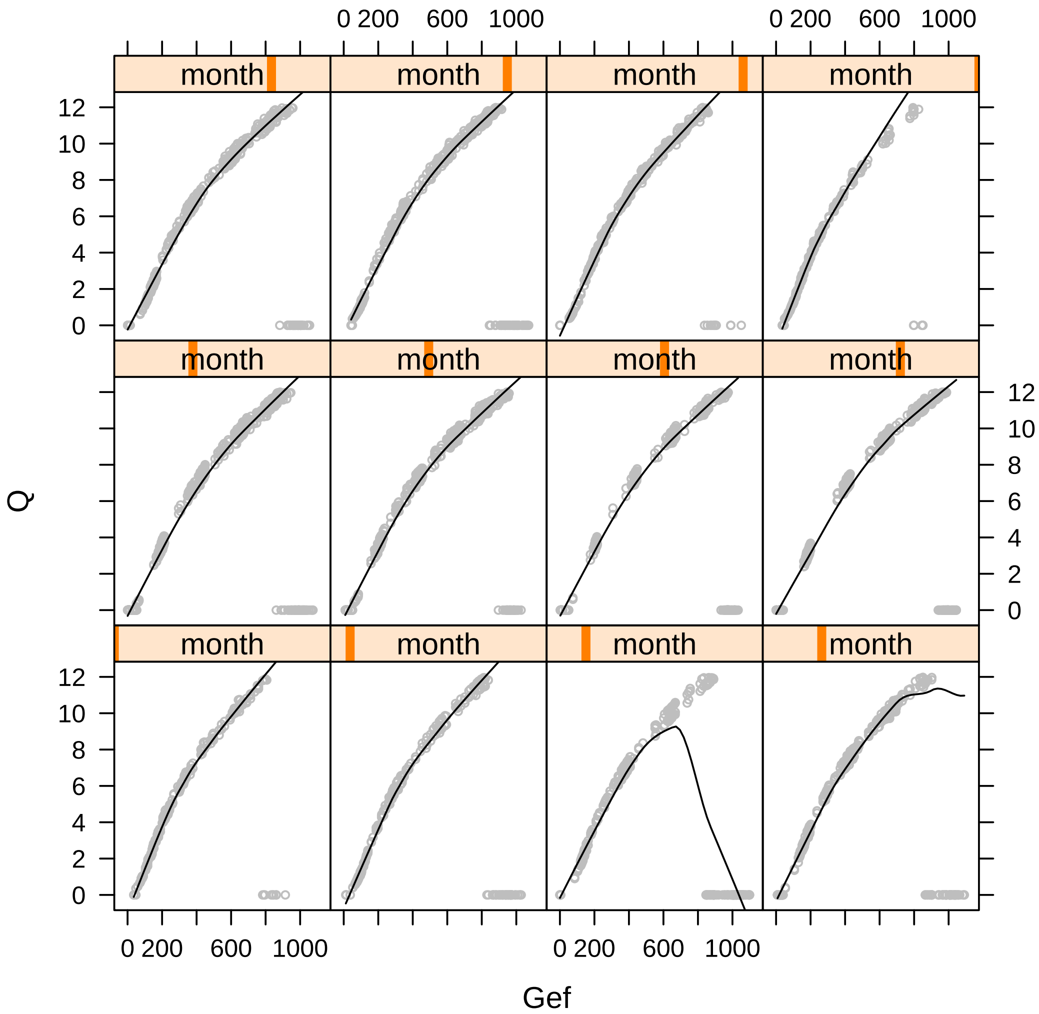

Figure 18: Water flow versus irradiance of a PVPS system with a SP8A44 pump and a generator of 7000 Wp with a manometric height of 50 meters.

```
> p = xyplot(prodStat$stat)
> print(p)
```

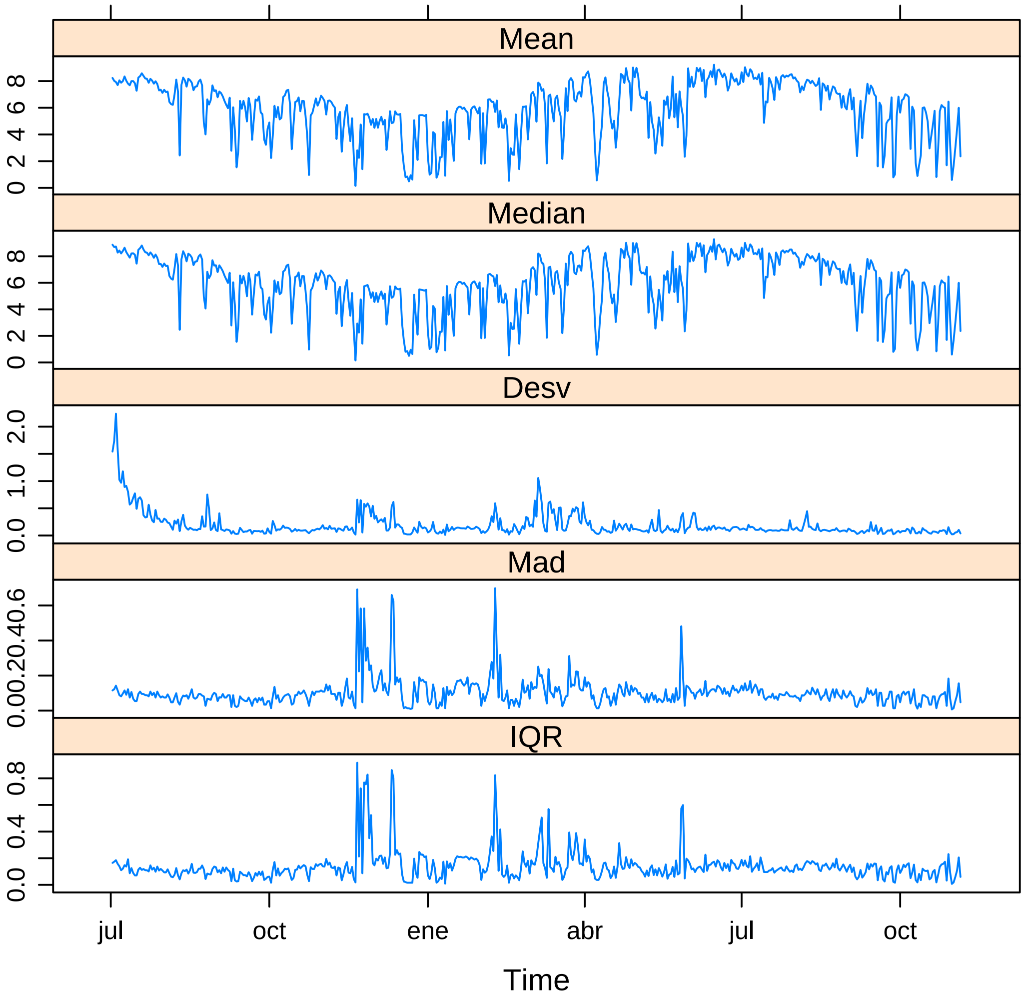

Figure 19: Statistical analysis of a set of 22 PV systems.

```
> day = as.Date("2008-8-29")
> ndays = c(5, 10, 15, 20)
> palette = brewer.pal(n = length(ndays), name = "Set1")
> TDColor <- TargetDiagram(prodEx, end = day, ndays = ndays, color = palette)
> print(TDColor$plot)
```

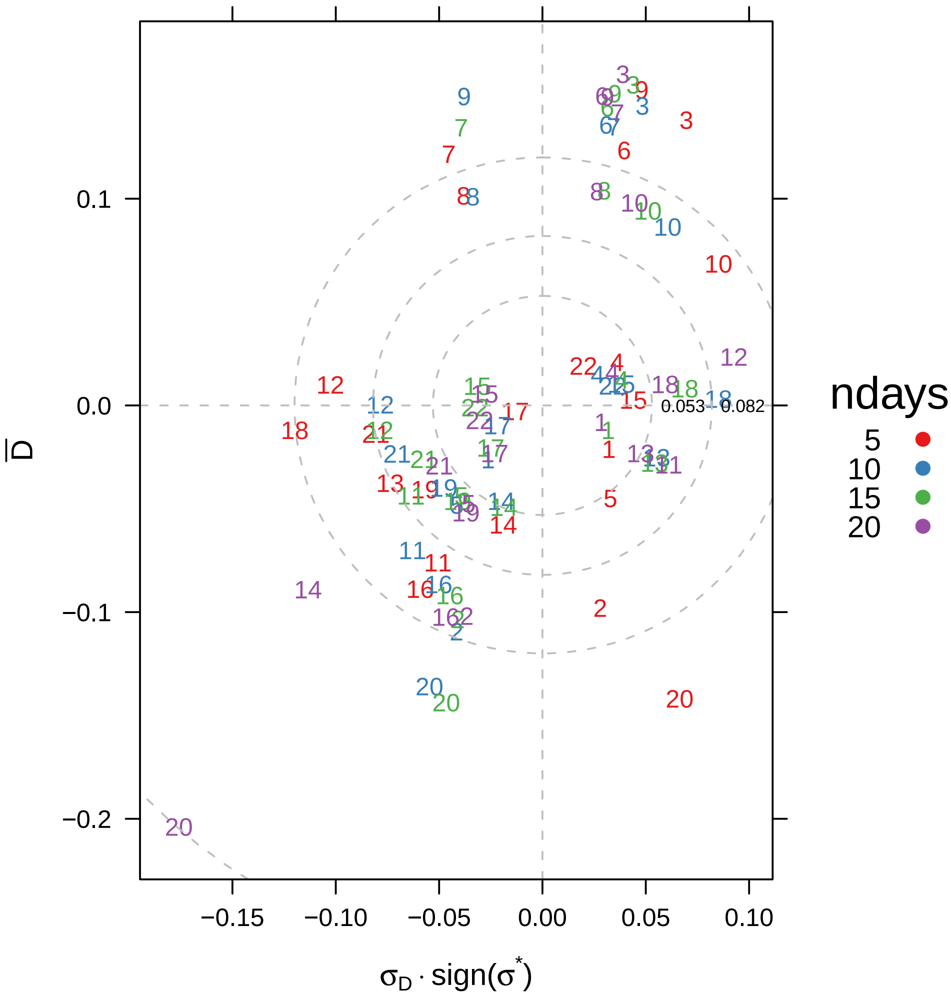

Figure 20: "Target Diagram" of the statistical analysis of a set of 22 systems during various time periods.

References

[1] M.~Alonso Abella, E.~Lorenzo, and F.~Chenlo. Pv water pumping systems based on standard frequency converters. *Progress in Photovoltaics: Research and Applications*, 11(3):179–191, 2003.

[2] Thomas~A. Huld, Marcel Súri, Ewan~D. Dunlop, and Fabio Micale. Estimating average daytime and daily temperature profiles within europe. *Environmental Modelling & Software*, 21(12):1650 – 1661, 2006.

[3] N.~Martin and J.~M. Ruíz. Calculation of the pv modules angular losses under field conditions by means of an analytical model. *Solar Energy Materials & Solar Cells*, 70:25–38, 2001.

[4] J.~K. Page. The calculation of monthly mean solar radiation for horizontal and inclined surfaces from sunshine records for latitudes 40n-40s. In *U.N. Conference on New Sources of Energy*, volume~4, pages 378–390, 1961.

[5] D.~Panico, P.~Garvison, H.~J. Wenger, and D.~Shugar. Backtracking: a novel strategy for tracking pv systems. In *IEEE Photovoltaic Specialists Conference*, pages 668–673, 1991.

[6] O.~Perpiñán. *Grandes Centrales Fotovoltaicas: producción, seguimiento y ciclo de vida*. PhD thesis, UNED, 2008.

[7] O.~Perpiñán. Statistical analysis of the performance and simulation of a two-axis tracking pv system. *Solar Energy*, 83(11):2074–2085, 2009.

[8] A.~Zeileis and G.~Grothendieck. zoo: S3 infrastructure for regular and irregular time series. *Journal of Statistical Software*, 14(6):1–27, 2005.