SINGLE DISH EXPOSURE TIME CALCULATOR
User Manual

Release 1.0

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in collaboration with the SRT Astrophysical Validation Team*

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1 Introduction

In 2006, a group of IRA staff started working at the realization of tools that may be useful in proposal preparation for single dish observations with the Medicina 32m telescope. The first developed tool was a simple version of an Exposure Time Calculator (ETC) for the Medicina antenna that was made publicly available in 2006 on the IRA web pages. With the advent of the new Enhanced Single Dish Control System for single dish observations, in the following years more sophisticated functionalities have been added to the ETC to include the newly available observing modes, like the on-the-fly mapping. In 2012 a version of the ETC including the Sardinia Radio Telescope was internally released to the scientific and technical commissioning groups of the SRT. Finally, in November 2014 the first version of the Exposure Time Calculator including both Medicina and SRT was made publicly available to the scientific community at this web address: http://www.ira.inaf.it/expotime/all_ETC.html. It is planned to add to the ETC also the Noto telescope in the near future.

This document aims at describing the formulae and computations performed by the ETC considering the different observing modes and strategies, and is intended to be a Reference Manual for the users. Specific characteristics related to observations with Medicina or SRT are mentioned in the text when appropriate.

In Section 2 an overall description of the ETC observing modes and of the web interfaces currently available for the various telescopes is given. The basic formulae are illustrated in Sect. 3, while in Sects. 4, 5 and 6 computations for radiometer/position switching, On-The-Fly Cross Scans and On-The-Fly Mapping modes respectively are detailed. The input and output parameters are described in Subsections for each observing mode.

2 ETC Overview

The Exposure Time Calculator provides an estimate of the exposure time needed to reach a given sensitivity (or vice versa) under a set of assumptions on the telescope setup and the observing conditions. The ETC main page is shown in Fig. 1. From this page, the user first selects the desired telescope and observing mode and the corresponding web form is loaded. The foreseen observing modes are total power and spectropolarimetry, and their availability at a given telescope is determined by its current instrumental setup.

Figure 1: ETC main page.

The web forms for the two observing modes are shown in Figures 2 and 3. In both cases, the user is required to fill in values for a set of parameters related to the frontend, backend and observational conditions. This last class of parameters includes information on the season, the source elevation and the geometry of the observation, as well as inputs related to the astrophysical source like its shape and size. In all cases, the user can provide in input the desired sensitivity or the total exposure time. In the first case the ETC will compute the total exposure time needed to reach the given sensitivity, while in the second case the sensitivity that can be reached in the given exposure time will be evaluated.

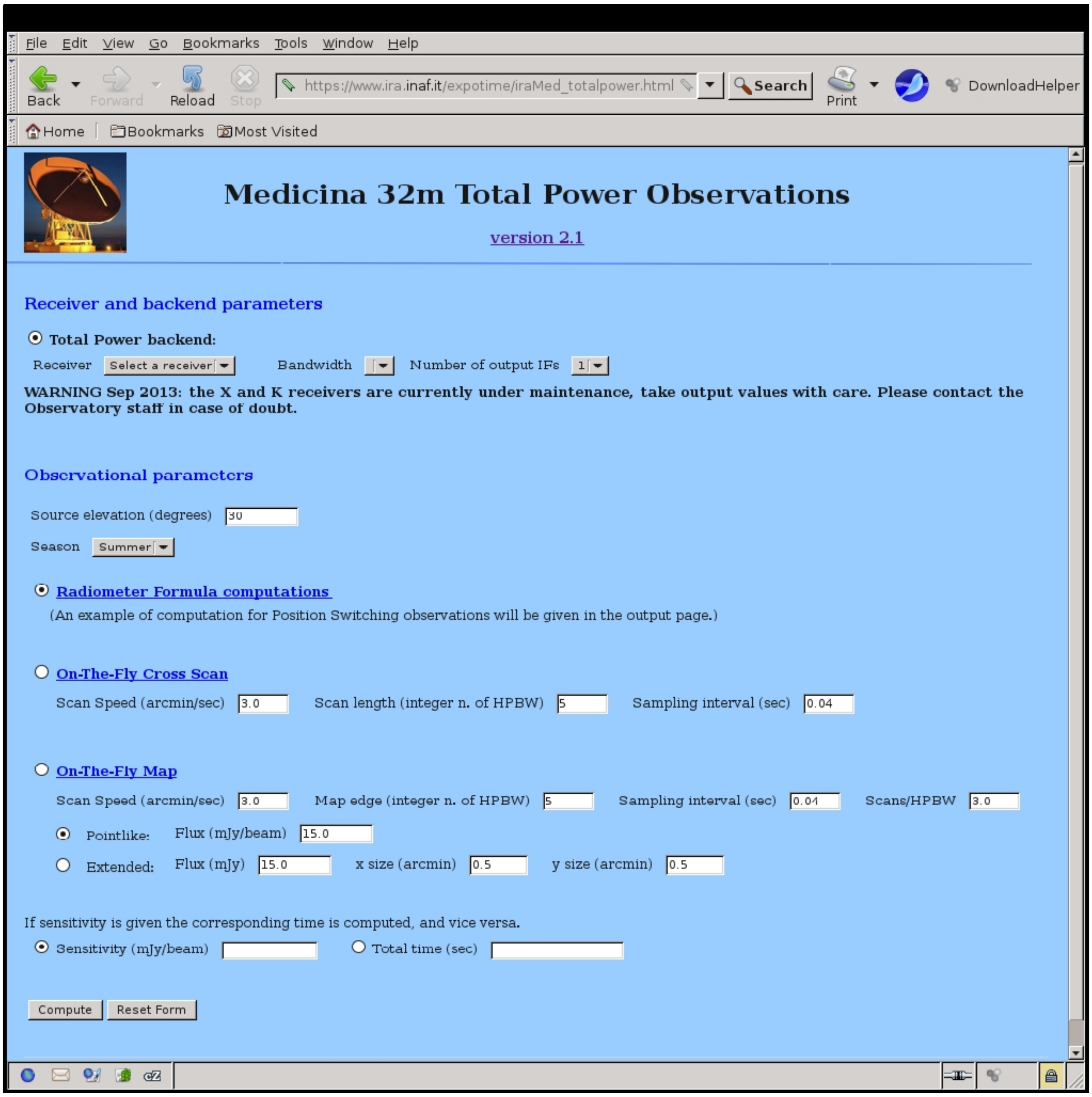

Figure 2: ETC web page for total power observations.

Three different geometries for the observations are currently implemented: radiometer formula/position switching - where radiometer formula computations can be seen as an on-source or stare observing mode, on-the-fly cross scan and on-the-fly map. The meaning of the required sensitivity/exposure time varies according to the selected observing geometry as detailed in the following sections.

The ETC output, besides a summary of the user-selected input parameters, consists in a number of parameters that describe the computational results and that may be useful to better plan the observations.

An on line manual is provided in the ETC main page together with telescope manuals and tables summarizing the calibration coefficients in use. Main parameters in the input web forms are also linked to specific sections of the online manual to facilitate the users.

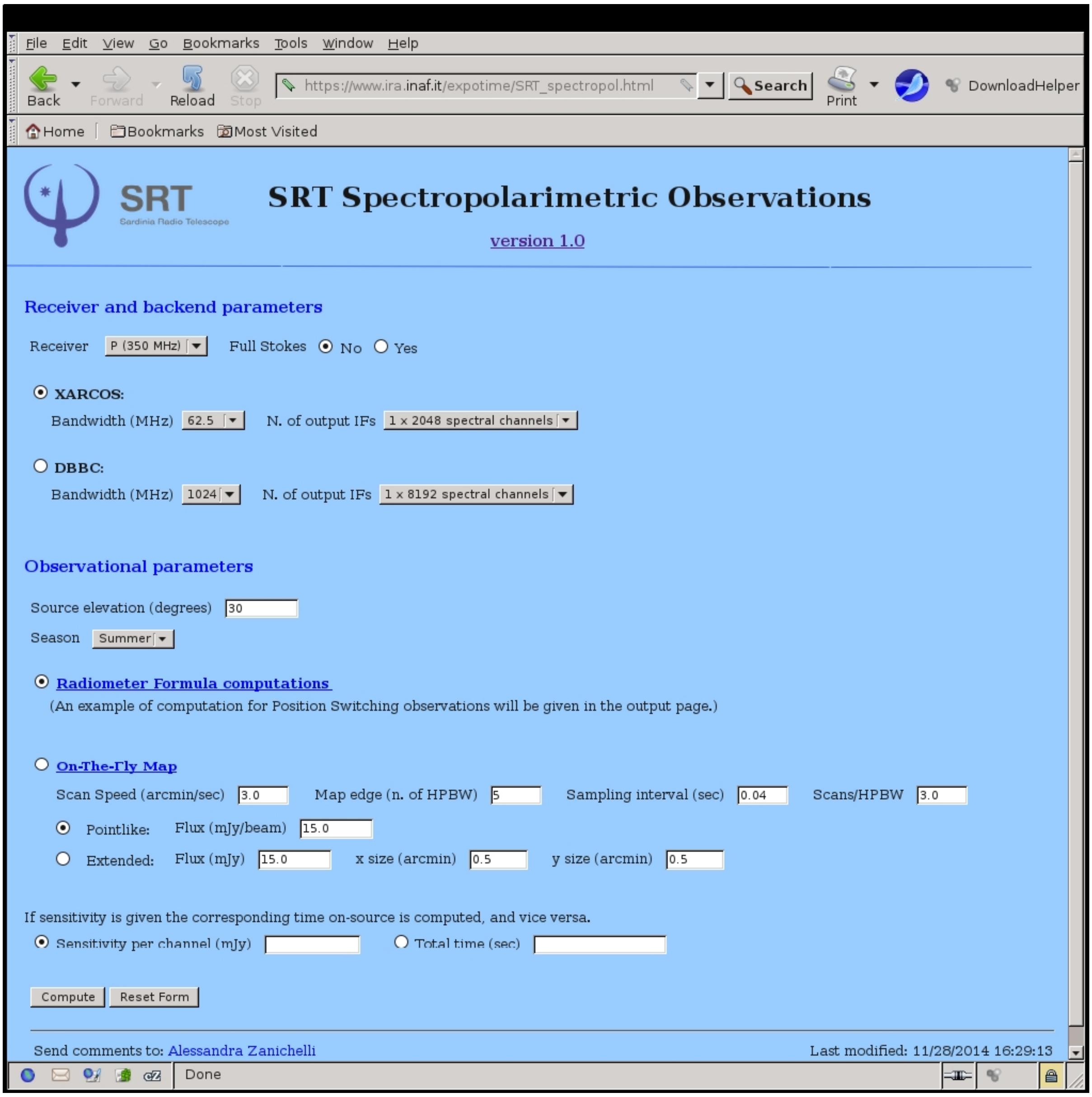

Figure 3: ETC web page for spectropolarimetric observations.

3 Basic Formulae

The basic formula for the ETC is the so-called radiometer formula:

$$t_{TOT} = \left(\frac{T_{sys}}{G \times \sigma_{TOT}} \right)^2 \frac{1}{totBand}$$

where:
t_{TOT} = exposure time (sec).
T_{sys} = system temperature (K);
G = gain (K/Jy);
σ_{TOT} = sensitivity (Jy).
$totBand$ = total observed bandwidth (Hz).

3.1 Bandwidth

The term $totBand$ has different values depending on the observing mode:

Continuum (no polarimetry):	$totBand = \Delta\nu \times N_{IF}$
Polarimetry:	$totBand = 2 \times \Delta\nu$
Spectroscopy (no polarimetry):	$totBand = \Delta\nu_{ch} \times N_{IF}$
Spectropolarimetry:	$totBand = 2 \times \Delta\nu_{ch}$

where:
$\Delta\nu$ = observed bandwidth (Hz);
$\Delta\nu_{ch}$ = spectroscopic channel bandwidth (Hz);
N_{IF} = number of IF.
In the following computations, $totBand$ assumes the value corresponding to the user-selected observing mode.

3.2 System Temperature

Theoretically, the system temperature of a telescope changes with the telescope elevation according to the atmospheric emission, following:

$$T_{sys} = T_{rec} + T_{atm} = T_{rec} + \left[T_m \left(1 - e^{\frac{-\tau}{sin(El)}}\right)\right]$$

where:
T_{rec} = receiver temperature (K);
T_{atm} = atmospheric brightness, expressed as a temperature (K);
T_m = average atmospheric temperature which takes into account also the effects of the higher trophospheric layers (K);
τ = atmospheric opacity;
El = source elevation at the epoch of the observation.
For receivers working below 22 GHz we assume that the seasonal variations of the atmospheric opacity are negligible, and system temperature is given in the form of tabulated values as a function of source elevation only. In this case, the user gives in input to the ETC the elevation at which the observation will be conducted (see next paragraphs) and the ETC selects among tabulated values the T_{sys} best matching the user-selected elevation.
When observing at 22 GHz, the seasonal variation of the atmospheric opacity is explicitly taken into account in the T_{sys} computations. In such cases, the user selects both the source elevation and the season of the observation. Average opacity values for the various seasons (Spring, Summer, Autumn, Winter) are available in the ETC database and are selected on the basis of the ETC user-input parameters. For SRT, we use seasonal tabulated values also for T_m, while for Medicina we adopt a fixed $T_m = 290$ K throughout the year.

3.3 Receiver Gain

Receiver gain is computed differently for SRT and Medicina telescopes. For Medicina, the ETC uses the polynomial formula:

$$G(El) = DPFU \times \left[(a \times El)^2 + (b \times El) + c\right]$$

where El is the source elevation and $DPFU$, a, b, and c are tabulated coefficients for each receiver.
In the case of SRT, gain is approximately constant at any elevation as it employs active mirrors, thus each receiver is characterized by a single gain value which is used by the ETC without the need to apply the above formula.

4 Radiometer Formula + Position Switching Computations

Computations in this case are done by simply applying the radiometer formula to the user-selected values. In this case, the input sensitivity/exposure time are intended to be on-source. In addition, an example of Position Switching observation is evaluated, assuming to perform an ON-OFF-OFF-ON cycle. Figure 4 illustrates the geometry of a Position Switching observation.

Figure 4: Example of a Position Switching observation.

The ON position corresponds to the on-source one, while the OFF observation is executed at a nearby position on the empty sky. The OFF position is assumed to be at a distance of 5 beamsizes from the ON one. An ON-OFF-OFF-ON sequence is assumed to minimize the time requested to move the telescope between consecutive positions.

4.1 Input Parameters

The user provides in input:

1) the desired sensitivity σ_{TOT} (mJy) OR the desired time t_{TOT} (sec).

4.2 Computations: given $\sigma_{\mathbf{TOT}}$ evaluate $\mathbf{t_{TOT}}$

The radiometer formula is used to compute the exposure time needed to reach a given sensitivity:

$$t_{TOT} = \left(\frac{T_{sys}}{G \times \sigma_{TOT}}\right)^2 \frac{1}{totBand}$$

4.3 Computations: given $\mathbf{t_{TOT}}$ evaluate $\sigma_{\mathbf{TOT}}$

By reverting the radiometer formula:

$$\sigma_{TOT} = \left(\frac{T_{sys}}{G}\right) \sqrt{\frac{1}{totBand \times t_{TOT}}}$$

4.4 Position Switching computations

An example case for Position Switching observations is also computed as a particolar case for the radiometer formula mode.
For Position Switching computations we assume a cycle of four exposures acquired in the sequence: ON-OFF-OFF-ON and combined as $[(ON_1\text{-}OFF_1) + (ON_2\text{-}OFF_2)]/2$ to get the final result. We also assume that the time spent on each position is the same ($t_{ON} = t_{OFF}$), that measurements are independent and that they have identical uncertainties.
The r.m.s. on the frame resultant from one (ON-OFF) subtraction is:

$$\sigma_{ON-OFF} = \sqrt{\sigma_{ON}^2 + \sigma_{OFF}^2} = \sigma_{ON} \times \sqrt{2}$$

The r.m.s. on the frame resultant from the average of the two (ON-OFF) subtractions, i.e. the r.m.s. of one ON-OFF-OFF-ON cycle is, according to the error propagation for the mean:

$$\sigma_{cycle} = \sqrt{\frac{1}{2} \times \sigma_{ON-OFF}^2} = \sqrt{\frac{1}{2} \times 2 \times \sigma_{ON}^2} = \sigma_{ON}$$

A) If the user-selected input sensitivity is intended to be reached in one complete ON-OFF-OFF-ON cycle of Position Switching, i.e. $\sigma_{cycle} = \sigma_{TOT}$, t_{cycle} is computed as:

$$t_{cycle} = 2 \times (t_{ON} + t_{OFF} + t_{shift}) + t_{prep}$$

The value of $t_{ON} = t_{OFF}$ is computed by obtaining σ_{ON} from the above equation for σ_{cycle} and applying the:

$$t_{ON} = \left(\frac{T_{sys}}{G}\right)^2 \frac{1}{\sigma_{ON}^2 \times totBand}$$

The other terms in t_{cycle} are: t_{prep}, which is the instrument setup time, **currently set to zero for Medicina and SRT telescopes (as of ETC v1.0)** and t_{shift}, the slewing time needed to move from one position to the next. The value for t_{shift} is computed by means of the uniformly accelerated motion formula assuming that the OFF position is 5 beamsizes away from the ON position:

$$t_{shift} = \sqrt{(5 \times HPBW)\ \frac{2}{MaxAcc}}$$

The value of the maximum acceleration is set inside the ESCS/Nuraghe CommonDataBase (CDB). For Medicina and SRT we consider as maximum values for the acceleration along the scan axis $MaxAcc = 0.4$ deg/sec^2 and $MaxAcc = 0.25$ deg/sec^2 respectively. These values have been set to be significantly lower than the actual maximum accelerations allowed by the mount motors, in order to guarantee a smooth and precise execution of the acceleration ramp.

B) In the opposite case in which the user-selected input exposure time is intended to be used for the execution of a complete ON-OFF-OFF-ON cycle of Position Switching, $t_{cycle} = t_{TOT}$. The value for σ_{ON} to be inserted in the σ_{cycle} equation is evaluated as:

$$\sigma_{ON} = \left(\frac{T_{sys}}{G}\right) \sqrt{\frac{1}{totBand \times t_{ON}}}$$

where t_{ON} is obtained by reverting the equation for t_{cycle}:

$$t_{ON} = [t_{cycle} - (2 \times t_{shift}) - t_{prep}]/4$$

4.5 Output Parameters

When selecting the radiometer formula computations, the following parameters are given in output:

- Receiver gain (K/Jy), system temperature (K) and beam HPBW (arcmin) taken from tabulated values for the selected receiver.
- Actual elevation (deg) used for computations: this parameter may slightly differ from the user-selected one. Values for T_{sys} are tabulated at different values of the elevation, typically every 5 degrees. Among the tabulated values, the ETC looks for the T_{sys} which was measured at the elevation closest to the user-selected one.
- Estimate of the Confusion Noise (mJy) at the selected frequency (not yet implemented for Medicina).
- Time on Source (sec) or Sensitivity (mJy) computed according with the selected input values.
- Example case for Position Switching Observations, in which an estimate of the total time needed to complete an ON-OFF-OFF-ON cycle is given. This estimate currently does not include the system setup time.

5 On-The-Fly Cross Scan computations

Each scan is composed by two orthogonal subscans, to form a cross: the source is supposed to be located at the intersection of the cross. To reach a given sensitivity (or exposure time) many consecutive Cross Scans may be required.
An example of Cross Scan geometry is shown in Figure 5, where two consecutive crosses are executed over the same position (the small displacement between the blue and red crosses is for visualization purposes) and each arrow represents a subscan.

5.1 Input Parameters

For OTF Cross Scan computations the user provides in input:

1) the length of each subscan: *subscanLength* (expressed in units of HPBW for the selected receiver);

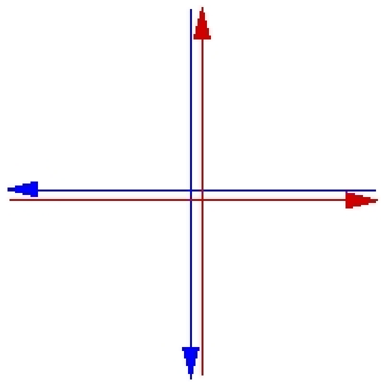

Figure 5: Example of two Cross Scan observations (red and blue), each consisting of two orthogonal subscans.

2) the constant scan speed at which the telescope moves while scanning: $scanSpeed$ (arcmin/sec, equivalent to deg/min);

3) the time interval between two subsequent data samples: $sampleInterval$ (sec);

4) the desired total sensitivity over an HPBW, i.e. the final sensitivity σ_{TOT} (mJy/beam) to be reached by integrating a suitable number of Cross Scans, OR the total time t_{TOT} (sec) one wants to observe executing OTF Cross Scans.

IMPORTANT NOTES:
1) If the user provides a sensitivity and wants to know the time necessary to reach it, the sensitivity is intended to be reached over 1 HPBW by performing OTF Cross Scan observations for a total duration equal to the computed time. That means time is not on-source, but is the overall duration of the observation including inter-subscan and intra-subscan times (a priori known). Accordingly, if the user provides a time interval and wants to know to which sensitivity it corresponds to, this time is intended as the total time needed to perform all the subscans necessary to reach the given sensitivity over an HPBW, including inter-subscan and intra-subscan times.

2) Effective values for t_{TOT} and σ_{TOT} may slightly differ from the input requested values because of some approximations done in the ETC code. For instance, the user may require a sensitivity that would be reached by executing exactly 2.2 Cross Scans, but currently the ETC approximates to the nearest integer, that is it would consider that just 2 Cross Scans are needed and on this basis the needed exposure time is computed. As an example, to reach a sensitivity of 8 mJy/beam in an OTF Cross Scan mode observation with Medicina Total Power backend, CC receiver with 150 MHz band and $N_{IF} = 1$, scan speed of 3 arcmin/sec, scan length of 5 HPBW and sampling interval of 0.04 sec, the ETC v 1.0 requires the execution of only one Cross Scan, whose effective sensitivity is 9.253 mJy/beam (while the desired input sensitivity of 8 mJy would be reached with 1.3 OTF Cross Scans). The *effective* total sensitivity or the *effective* total time are thus re-computed, starting from the desired ones and taking into account the observing setup.

3) In case the given sensitivity can be reached in a time shorter than that needed to execute just one Cross Scan (or the given exposure time is shorter than that needed to complete one Cross Scan) a warning message is issued in output.

5.2 Computations: given $\sigma_{\mathbf{TOT}}$ evaluate $\mathbf{t_{TOT}}$

The total time t_{TOT} needed to reach the desired sensitivity σ_{TOT} over the HPBW area is given by:

$$t_{TOT} = [(2 \times subscanDuration) + deadTime] \times n_{crossScans}$$

Where:
$n_{crossScans}$ = total number of Cross Scans that must be executed to reach the desired sensitivity;
$deadTime$ = time which is not spent acquiring data during the execution of one Cross Scan.

To evaluate t_{TOT} we must compute: $deadTime$, $subscanDuration$ and $n_{crossScans}$.

- Evaluate deadTime:
The parameter *deadTime* is the time which is not spent acquiring data during the execution of one Cross Scan. It is given by the sum of two terms: *interSubscanTime* and *intraSubscanTime*. The first term is given by the duration of the acceleration/deceleration ramps taking place before/after the actual subscans, and is determined as a function of the scanning speed and of a given fraction of the maximum acceleration allowed by the mount, specific for each telescope.
For Medicina and SRT we consider the maximum acceleration $MaxAcc$ to be 0.4 deg/sec^2 and 0.25 deg/sec^2 respectively, and we use **one tenth of the maximum acceleration to compute the ramps** (as the system itself does, to guarantee the maximum precision):

$$rampTime = \frac{speed}{0.1 \times MaxAcc} = \frac{speed}{0.025}$$

The execution of each subscan implies to perform 2 ramps, so:

$$interSubscanTime = \frac{2 \times speed}{0.025}$$

The term *intraSubscanTime* is an indicative intra-scan slewing time (i.e. performed at full $MaxAcc$), which takes into account the change in position among subscans. By reverting the formula for the uniformly accelerated motion ($s = \frac{1}{2}\, a\, t^2$) and considering that s (the intra-scan path) in this case is the hypotenuse of a triangle whose sides are the two half-subscans:

$$intraSubscanTime = \sqrt{\frac{\sqrt{2} \times subScanLength}{MaxAcc}} = \sqrt{\frac{\sqrt{2} \times subscanLength}{0.25}}$$

It is now possible to estimate the overall dead time for 1 Cross Scan: it is given by twice the *interSubscanTime* (two sub-scans form one Cross Scan) plus once the *intraSubscanTime* (the telescope changes position between subscans once per Cross Scan).

$$deadTime = (2 \times interSubscanTime) + intraSubscanTime$$

- Evaluate subscanDuration:
The duration of a single subscan is easily computed as:

$$subscanDuration = subscanLength \; / \; scanSpeed$$

where we recall that *subscanLength* is given in units of HPBW (see Sect. 5.1).

- Evaluate $n_{crossScans}$**:**
First compute $t_{totHPBW}$ = time spent on 1 HPBW to reach the desired sensitivity σ_{TOT}:

$$t_{totHPBW} = \left(\frac{\sigma^2_{HPBW,singleSubscan}}{\sigma^2_{TOT}} \right) t_{HPBW}$$

Where the time spent on HPBW during each subscan is:

$$t_{HPBW} = HPBW/scanSpeed$$

The sensitivity over an HPBW for each subscan is given by:

$$\sigma_{HPBW,singleSubscan} = \sigma_i \sqrt{\frac{sampleInterval}{t_{HPBW}}}$$

And σ_i, given by the radiometer formula, is the sensitivity per sampling interval:

$$\sigma_i = \left(\frac{T_{sys}}{G} \right) \sqrt{\frac{1}{totBand \times sampleInterval}}$$

Where *totBand* takes the value proper to the observing mode, as defined in Section 3.

Having computed the time that is necessary to spend over one HPBW area to reach the σ_{TOT} sensitivity, the number of necessary subscans is computed dividing it by the time spent on one HPBW during each subscan.

$$n_{subscans} = \frac{t_{totHPBW}}{t_{HPBW}}$$

The number of complete Cross Scans (i.e. the number of couples of orthogonal subscans)is:

$$n_{crossScans} = (n_{subscans} + 1)/2$$

Results are rounded up in order to always obtain an integer number of complete Cross Scans.

5.3 Computations: given $\mathbf{t_{TOT}}$ evaluate $\sigma_{\mathbf{TOT}}$

The parameter t_{TOT} is the overall observing time and thus includes also *deadTime*. The actual sensitivity σ_{TOT} must be computed using the effective time spent on Cross Scans, i.e. excluding *intraSubscanTime* and *interSubscanTime*. First we need to compute how many Cross Scans can be executed in the given t_{TOT}:

$$nCrossesInExptime = \frac{t_{TOT}}{singleCrossTotalTime}$$

where *singleCrossTotalTime* is the total time to execute one Cross Scan (including its overheads):

$$singleCrossTotalTime = (2 \times subscanDuration) + deadTime$$

and *deadTime* is computed as in Sect. 5.2. The value of *nCrossesInExptime* is rounded to the nearest integer. The sensitivity σ_{TOT} is thus:

$$\sigma_{TOT} = \frac{\sigma_{HPBW,singleSubscan}}{\sqrt{nCrossesInExptime}}$$

5.4 Output Parameters

When selecting the On-The-Fly Cross Scan computations, the following parameters are given in output:

- Receiver gain (K/Jy), system temperature (K) and beam HPBW (arcmin) from tabulated values for the selected receiver.
- Actual elevation (deg) used for computations: this parameter may slightly differ from the user-selected one. Values for T_{sys} are tabulated at different values of the elevation, typically every 5 degrees. Among the tabulated values, the ETC looks for the T_{sys} which was measured at the elevation closest to the user-selected one.
- Estimate of the Confusion Noise (mJy) at the selected frequency (not yet implemented for Medicina).
- Total Time (sec) and Sensitivity (mJy/beam) for 1 Cross Scan. These are the time needed to complete 1 Cross Scan and the sensitivity that can be reached over 1 Cross Scan. They are computed, according to the quantities derived above, as *singleCrossTotalTime* and $singleCrossRms = \sigma_{HPBW,singleSubscan} \,/\, \sqrt{2}$.
- Total number of Cross Scans: the number of Cross Scans *nCrossesInExptime* (each one being made of a couple of orthogonal subScans) to be executed and combined in order to reach the desired input sensitivity / exposure time. A minimum of 1 Cross Scan is imposed.
- Total dead Time (sec) is the dead time spent for the execution of the required number of Cross Scans, i.e. $deadTime \times nCrossesInExptime$. It takes into account the slewing time plus the acceleration/deceleration ramps.
- Total OTF Cross Scan Time (sec) is the total observing time that is needed to reach the user-selected sensitivity over *nCrossesInExptime* Cross Scans. Conversely, Total OTF Cross Scan sensitivity (mJy/beam) is the sensitivity obtained over *nCrossesInExptime* Cross Scans given the user-selected observing time.

- Effective Total OTF Cross Scan Time (sec) or Effective Total OTF Cross Scan sensitivity (mJy/beam). These numbers are computed to account for some approximations made by the code that may affect the planning of the observations. For instance, currently the number of Cross Scans is rounded to the nearest integer (not rounded *upwards* to the nearest integer), thus the effective total sensitivity or the effective total time are re-computed, starting from the desired ones and taking into account the observing setup. Effective values may slightly differ from the input requested values because of the above approximations, see also notes in Sect. 5.1.

6 On-The-Fly Map computations

Each map is composed by a sequence of back-and-forth On-The-Fly subscans. Each subscan is shifted with respect to the previous one in order to fully cover the desired sky region.
An example of On-The-Fly Map geometry is shown in Figure 6, where each arrow represents a subscan.

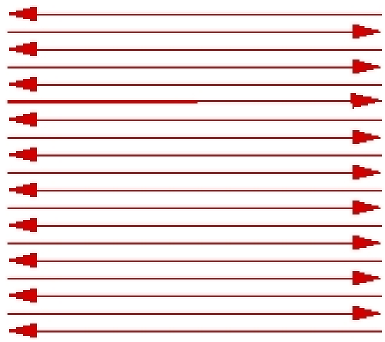

Figure 6: Example of an On-the-Fly Map observation.

6.1 Input Parameters

For OTF Map computations the user provides in input:

1) the scan speed at which the telescope moves during the Cross Scan: $scanSpeed$ (arcmin/sec, equivalent to deg/min);

2) the time interval between two subsequent samples: $sampleInterval$ (sec);

3) the map edge, i.e. the map span on each side of the source, expressed in number of HPBW: $mapEdge$. The source size and $mapEdge$ are used to compute the size of the map (see computations below).

4) the number of scans for each HPBW, corresponding to the HPBW sampling: $linesPerHPBW$.

5) source parameters:

    - source geometry: extended or pointlike;
    - source flux: $Flux$, in mJy/beam for pointlike sources or in mJy for extended sources (intended as the source integrated flux). Flux values are only used to compute the total S/N;
    - source sizes: for extended sources $size_x$, $size_y$ (arcmin). The size of pointlike sources is set by default to the HPBW value for the selected receiver. The source size and $mapEdge$ are used to compute the size of the map.

6) the desired total sensitivity over one HPBW, i.e. the sensitivity to be reached over an HPBW area, σ_{TOT} (mJy/beam). In this case the ETC computes how many OTF maps are needed to reach that sensitivity. Alternatively, one can provide the total time to be spent in OTF map mode with the selected observing setup, t_{TOT} (sec). In this case the ETC computes how many maps will be completed in that time interval and what value of the final sensitivity is going to be reached.

IMPORTANT NOTES:
1) Currently, square maps only are allowed. As detailed in Sect. 6.2, the maximum source size (i.e. one HPBW for pointlike sources or the maximum between $size_x$ and $size_y$ for extended sources) and $mapEdge$ are used to compute the size of the map.

2) if the user provides a sensitivity and wants to know the time necessary to reach it, the sensitivity is intended to be reached over an HPBW by performing OTF Map observations for a duration equal to the computed time. That means time is not on-source, but is the overall duration of the observation including "dead time" (a priori known). Accordingly, if the user provides a time and wants to know to which sensitivity it corresponds, time is intended as the total time needed to perform all the map observations necessary to reach the given sensitivity over an HPBW, including "dead time".

3) Effective values for t_{TOT} and σ_{TOT} may slightly differ from the input requested values because of some approximations done in the ETC code. For instance, the user may require a sensitivity that would be reached by executing exactly 2.2 OTF maps, but currently the ETC approximates to the nearest integer, that is it would consider that just 2 maps are needed and on this basis the needed exposure time is computed. Similarly, the ETC requires that at least one map is executed even if the desired sensitivity could be reached in a shorter time. As an example, to reach a sensitivity of 7 mJy/beam in an OTF Map mode observation of a pointlike source with Medicina Total Power backend, CC receiver with 150 MHz band and $N_{IF} = 1$, scan speed=3 arcmin/sec, map edge=5 HPBW, sampling interval of 0.04 sec, 3 scans per HPBW, the ETC v 1.0 requires the execution of only one OTF map, whose effective sensitivity is 7.555 mJy/beam (while the desired input sensitivity would be reached with 1.15 OTF maps). The *effective* total sensitivity or the *effective* total time are thus re-computed, starting from the desired ones and taking into account the observing setup.

6.2 Computations: given $\sigma_{\mathbf{TOT}}$ evaluate $\mathbf{t_{TOT}}$

The time t_{TOT} can be expressed as:

$$t_{TOT} = n_{map} \times t_1$$

where:
n_{map} = number of maps to be combined to reach σ_{TOT}.
t_1 = time needed to complete one map given the observing parameters, including dead time.

To evaluate t_{TOT} we must compute: n_{map} and t_1.

- Evaluate $\mathbf{n_{map}}$: The expression for σ_{TOT} can be written as:

$$\sigma_{TOT} = \frac{\sigma_1}{\sqrt{n_{map}}}$$

where σ_1 is the sensitivity reached over one HPBW in a single map assuming that each beam size is sampled with $linesPerHPBW$ points (i.e. $linesPerHPBW$ scans are needed to sample one HPBW). It can be easily computed by means of the sensitivity per HPBW reached in a single subscan:

$$\sigma_1 = \frac{\sigma_{HPBW,singlesubscan}}{\sqrt{linesPerHPBW}}$$

where the formula for $\sigma_{HPBW,singlesubscan}$ is the same as in the OTF Cross Scan case. By substituting σ_1 and σ_{TOT} in the above formula, the number of maps n_{map} can be evaluated.

- Evaluate $\mathbf{t_1}$: The time needed to complete 1 map, including dead time, is:

$$t_1 = (t_{singleScan} + deadTime) \times linesPerMap$$

where:

$$t_{singleScan} = mapSize \ / \ scanSpeed$$

$$linesPerMap = \frac{mapSize}{HPBW} \times linesPerHPBW$$

$$deadTime = interSubscanTime + intraSubscanTime$$

where now, differently to what happened in the OTF Cross Scan case for the computation of *deadTime*, the path to be performed in uniformly accelerated motion is exactly given by the transverse distance between two subscans (no more need to build a triangle). The parameter intraSubscanTime is thus:

$$intraSubscanTime = \sqrt{\frac{HPBW}{linesPerHPBW} \times \frac{2}{MaxAcc}}$$

Note that the formula for t_1 makes an approximation which has a negligible effect on computations. The correct one would be $t_1 = (t_{singleScan} + interSubscanTime)\, linesPerMap + intraSubscanTime\,(linesPerMap - 1)$ since the last subscan does not require additional turning time once completed.
Map size for pointlike sources is:

$$mapSize = HPBW + 2 \times (mapEdge \times HPBW)$$

While for extended sources:

$$mapSize = [max(size_x, size_y)] + 2 \times (mapEdge \times HPBW)$$

If the user select the extended source option but both the given source sizes happen to be smaller than the beamsize of the chosen receiver, the source is considered unresolved and *mapSize* is computed as for pointlike sources.
Finally, the Signal to Noise ratio over 1 HPBW area on the combined n_{map} is computed as:

$$\text{pointlike sources :} \quad \frac{S}{N} = \frac{Flux}{\sigma_{TOT}}$$

$$\text{extended sources :} \quad \frac{S}{N} = \left(\frac{Flux \times HPBWarea}{sourceArea}\right) \times \frac{1}{\sigma_{TOT}}$$

where:

$$sourceArea = \pi \times (0.5 \times size_x) \times (0.5 \times size_y)$$

$$HPBWarea = \pi \times (0.5 \times HPBW)^2$$

NOTE that the formula for extended sources gives an approximated result when $size_x$ or $size_y$ is sensibly smaller than $HPBW$ or the source is elongated and it actually does not fill "well" the beam. Results are accurate if the extended source completely fills the beam in both directions.

6.3 Computations: given $\mathbf{t_{TOT}}$ evaluate $\sigma_{\mathbf{TOT}}$

The parameter t_{TOT} is the overall observing time and thus includes also *deadTime*. The actual sensitivity σ_{TOT} must be computed using the effective time spent on the map, i.e. excluding *intraSubscanTime* and *interSubscanTime*. First we need to compute how many maps can be executed in the given t_{TOT}, rounded to nearest integer (and at least equal to 1):

$$n_{map} = \text{nearest integer}(t_{TOT} \;/\; t_1)$$

where t_1 is the time needed to complete one map given the observing parameters, including dead time, and is computed as in Sect. 6.2.
The sensitivity σ_{TOT} is thus computed as:

$$\sigma_{TOT} = \frac{\sigma_1}{\sqrt{n_{map}}}$$

where σ_1 is the sensitivity reached over one HPBW in a single map, computed as in Sect. 6.2.

6.4 Output Parameters

When selecting the On-The-Fly Map computations, the following parameters are given in output:

- Receiver gain (K/Jy), system temperature (K) and beam HPBW (arcmin) from tabulated values for the selected receiver.
- Actual elevation (deg) used for computations: this parameter may slightly differ from the user-selected one. Values for T_{sys} are tabulated at different values of the elevation, typically every 5 degrees. Among the tabulated values, the ETC looks for the T_{sys} which was measured at the elevation closest to the user-selected one.
- Estimate of the Confusion Noise (mJy) at the selected frequency (not yet implemented for Medicina).
- Map size (arcmin): maps are defined as squares centered on the source. Depending on the source geometry, the map size $mapSize$ is computed according to the above formulae.
- Number of subscans per map: depending on map and beam sizes and on the desired number of scans per HPBW the parameter $linesPerMap$ is computed.
- Total Time (sec) and Sensitivity (mJy/beam) for 1 Map. These are the quantities t_1 and σ_1 and refer to the time needed to complete one single map and to the sensitivity than can be reached on a single map.
- Total number of Maps: the number of maps n_{map} (each one being made of $linesPerMap$ subscans) to be executed and combined in order to reach the desired input sensitivity / exposure time. A minimum of 1 map is imposed.
- Total dead Time (sec) is the dead time spent for the execution of the required number of Maps, i.e. $deadTime \times n_{map}$. It takes into account the slewing time plus the acceleration/deceleration ramps. The parameter $deadTime$ is computed in a slightly different way than for the OTF Cross Scan case, see computations above.
- Total OTF Map Time (sec) is the total observing time needed to reach the user-selected sensitivity over n_{map} OTF maps. Conversely, Total OTF Map sensitivity (mJy/beam) is the sensitivity obtained over n_{map} OTF maps given the user-selected observing time.
- Effective Total OTF Map Time (sec) or Effective Total OTF Map sensitivity (mJy/beam). These numbers are computed to account for some approximations made by the code that may affect the planning of the observations. For instance, currently the number of maps is rounded to the nearest integer (not rounded *upwards* to the nearest integer), thus the effective total sensitivity or the effective total time are re-computed, starting from the desired ones and taking into account the observing setup. Effective values may slightly differ from the input requested values because of the above approximations, see also notes in Sect. 6.1.
- Source Signal-to-Noise Ratio over 1 HPBW area on the combined final map. This is the signal-to-noise ratio $\frac{S}{N}$ over n_{map} combined maps and inside a circular area of HPBW diameter. Depending on source geometry, it is computed in terms of source flux density and total sensitivity.

7 Confusion Noise computations

Confusion noise computations are currently implemented for SRT, and will be extended to the Medicina telescope in ETC version 1.1 to be released in summer 2015.
The rms width of the point-source confusion amplitude distribution calculated by Condon (1974) at the generic frequency ν is:

$$\sigma_{c,\nu} = \left(\frac{q^{3-\gamma}}{3-\gamma}\right)^{\frac{1}{\gamma-1}} \left(\frac{k\Omega_b}{\gamma-1}\right)^{\frac{1}{\gamma-1}} \left(\frac{\nu}{\nu_0}\right)^{-\alpha}$$

where q is the signal-to-noise ratio under which we expect confusion, Ω_b the beam solid angle, α the spectral index (with $S = S_0\nu^{-\alpha}$), and k and γ are the parameters of the power-law differential source counts calculated at the frequency ν_0:

$$n_{\nu_0}(S) = kS^{-\gamma}$$

Note that for the ETC computations we assumed q = 5.
To calculate the rms confusion at various frequencies the following power-law differential counts have been used:

- at 1.4 GHz we used the distribution given by Bondi et al. (2003) for $S > 0.6$ mJy:

$$n_{1.4\,\mathrm{GHz}} = (75.86 \pm 1.08) \left(\frac{S}{mJy}\right)^{-(1.79\pm0.05)} \mathrm{mJy}^{-1}\mathrm{deg}^{-2}$$

- at 5 GHz we extrapolated the confusion limit from the distribution at 1.4 GHz given by Bondi et al. (2003) for $S < 0.6$ mJy

$$n_{1.4\,\mathrm{GHz}} = (57.54 \pm 1.07) \left(\frac{S}{mJy}\right)^{-(2.28\pm0.04)} \mathrm{mJy}^{-1}\mathrm{deg}^{-2}$$

- at 20 GHz, we extrapolated the confusion limit from the distribution at 15 GHz given by Davies et al. (2011) for 0.5mJy $< S <$ 2.8mJy:

$$n_{15\,\mathrm{GHz}} = 376 \left(\frac{S}{Jy}\right)^{-1.80} \mathrm{Jy}^{-1}\mathrm{sr}^{-1}$$

- at 327 MHz, we extrapolated the confusion limit from the distribution at 333 MHz obtained by fitting the differential normalized source counts versus the flux given by Owen et al. (2009):

$$n_{333\mathrm{MHz}} = 1546 \left(\frac{S}{\mathrm{Jy}}\right)^{-1.88} \mathrm{Jy}^{-1}\mathrm{sr}^{-1}$$

References

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