PRESTO - Preservation Technologies for European Broadcast Archives

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AUDIO KEY LINKS:
PLAYBACK DEVICES IMPROVEMENT

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# 1. Summary

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2. Introduction

The present Deliverable includes a report on the results of implementation of the audio key links related to the analog part of the transcription chain individuated and described in Deliverable 3.2, section 4.5. The analysis performed then revealed two areas of work: the identification and assembly of a reference turntable to be employed in all the vinyl transcription chains and the selection of optimal analog to digital conversion technology. The two items touch different optimisation aspects of the analog part of the transcription chain, as the former is related to the improvement of the chain efficiency, by introducing automation and flexibility, and to the acquisition of know-how about key equipment that are disappearing from the market, while the latter has a direct impact on the quality of the signal that is captured by the transcription process, and that will be preserved in future.
3. Turntable automation

3.1. Key Link description and requirements

Turntable automation has been identified as a requirement for the implementation of efficient massive vinyl transcription chains. The expected advantage of turntable automation consists of the possibility of parallel management of several transcription lines by a single operator, as the transcription can be automatically started with a single key press on the transcription control computer, without having to manually position the pickup on the record, while the end is automatically detected by a sensor, relieving the operator from the need to continuously monitor the position of the pickup on the record.

The transcription chain for 78 RPM has further requirements as the records were produced in absence of standard. Several different parameters could have been employed that require a proper matching in the reproduction equipment. The main implications are on the geometry of the pick up, on the reproduction speed and on the equalization applied. While errors on speed and equalization can be effectively compensated with a suitable digital post-processing, and therefore, be moved off-line with respect to the main transcription chain, reading the record with an inappropriate pickup results in the loss of signal details that cannot be recovered at a later stage.

To avoid the need for switching stylus or cartridge between the transcription of an item and the next, it is convenient to fit two tone arms on a single turntable, so that two styli configurations can be tried on the fly without any reconditioning of the chain.

These requirements have been considered critical for commercially available equipment if combined with those relative to the reproduction quality, the robustness of the equipment and the product and the forecast of spare parts availability in the next years.

A market survey has shown that the choice of commercial turntables is drastically reduced to a scant number of semi-professional products if start/stop automation is required. Furthermore, if two tone arms are required, the list is reduced practically to zero. Few small companies have given their availability to modify their standard equipment according to user specifications, but no guarantee can be given about the continuity in time of the supply.

3.2. System overview

The above requirements, fully described in Deliverable 3.2, bring to the identification of a reference turntable, whose schematic representation is shown in figure 1. The platter rotation is controlled by a microcontroller that sends start and stop commands to the motor and monitors the actual rotation speed. Two tonearms can be installed on the chassis, each of which equipped with an automatic arm lift and a position sensor. Both the lift motor and the position sensor are connected to the microcontroller, which communicates with the transcription station via an RS232 interface. The commands, issued by the transcription station, are interpreted by the microcontroller that drives the motors that lift and lower the tonearms and controls the status of plate motor. When a tonearm reaches its parking position (end of the record) the microcontroller detects the event by monitoring the position sensor positioned on the tonearm and informs the transcription station, which in turn sends to the microcontroller the command relative to the arm lift and stops the acquisition, provided that no audio modulation is still present on the relative pick up, so that false end of record detections, typical of mechanical automatic stop devices, can be filtered out.
3.3. Adopted approach

Given the difficulty to guarantee the continuity of supply of commercial turntables compliant to the identified user requirements, and considering that the total number of pieces that the archive community could require of such equipment is probably not so high to justify the commercialisation of new products, it has been recognized that there is a convenience to acquire the necessary know how to assemble custom turntables, so that the assembly of small series can be commissioned to local companies, on the base of a reference prototype. Therefore, the adopted approach has been that of designing a prototype turntable, following the user requirements given in Deliverable 3.2, that can be used as a reference implementation for those who need to implement massive vinyl transcription chains. Of course, the design has not been started from scratch but, rather, it has been based on the assembly of high quality parts available on the market, whose production can be considered stable for the next years. Specific criteria followed in the selection of each key part are described in detail in the following section.

3.4. Components selection

Deck and Drive motor

Turntables can be roughly classified according to two characteristics: rigid or suspended frame and belt or direct drive. Broadcast equipment are generally of the type with rigid frame and direct drive, see as an example EMT 960 and Technics 1200 series. The main reasons for this configuration are the higher durability of the apparatus and the cost. More in detail, rigid frames offer an intrinsic robustness against accidental shoves and are therefore more suited to be placed in working environments than suspended frames that can easily be damaged. On the other hand, rigid frames provide poor environmental vibration insulation and must be carefully positioned in order to avoid that small knocks on the turntable body or the supporting furniture cause vibrations that will be captured by the pick up. Direct drive motors offer fast speed stabilisation at start up and lower maintenance requirements over belt drive motors. With quartz controlled motors, the wow and flutter is extremely low and thus doesn't represent a problem, while slight more concern is given to the microfluctuation of speed due to the PLL feedback correction. These fluctuations are better damped with belt transmission,
by means of elastic belts and high mass platters, than with direct transmission due to the lack of an elastic element to decouple the motor from the platter. Today, the only professional turntable produced in large quantities is the Technics SL-1210 MK2, current revised version of the basic 1200 model, widely employed in the broadcast and entertainment environments. The main features of this apparatus are listed in the table 1 below. Note that it doesn't fulfil our requirements under several aspects: 78 RMP speed is not available, double arm configuration is not possible as there is not enough space on the deck, the position of the arm is such that records larger than 12" cannot be fit and there is no arm lift automation. Furthermore, the external vibrations rejection has proven to be rather poor, due to the cheap plastic frame shell and insufficient damping feet. Nevertheless, the market leader position of Technics and the favourable quality to cost ratio make the 1210 a good starting point for the assembly of a compliant apparatus.

Several modifications need to be applied, both to the frame and to the electronics:
- The original frame shell cannot be used both for the insufficient damping and because of the difficulty to house two arms.
- The standard arm has also to be removed due to the difficulty of installing a lift automation and in favour of a higher quality and versatile arm, as described in the following section.
- A proper frequency oscillator must be added to implement 78 RPM speed and all the needed signal for start/stop automation must be derived.

**Tone arms**

SME Series 300 tonearms have been chosen (http://www.sme.ltd.uk). This series consists of three models, all with magnesium arm tube, differing only for the length of the arm, derived from the more expensive V Series, from which it differs mainly for the addition of a detachable headshell. The reasons for this choice are manifolds:
- SME has been a market leader in producing high end tonearms for about 40 years and its products are still in production and easily available.
- The pivoting mechanism is based on ball bearings that ensures more robust and economical arms than unipivot equivalents.
- Serie 300 has a detachable headshell that simplifies the cartridge replacement.
- The weight of the arms is such as to allow the use of both moving magnet (MM) and moving coil (MC) cartridges.
- A complete set of regulations make these arms suitable for the use with cartridges of different geometries without impacting on the deck mounting.

Specifically, Model 309 (the standard 9" arm) will be installed in replacement of the original Technics 1210 arm, to be used for 33 and 45 RMP record transcription, while Model 312 (12" long) will be mounted externally to the standard Technics deck in the 78 RPM version, where 2 tonearms are needed and a larger playing area must be provided to play older oversize records.

Both MC and MM cartridges can be mounted, but the high cost of MC cartridges, combined with the impossibility to substitute the stylus only, suggests that MM cartridges are a better choice for high transcription volumes. Among the choice of MM cartridges available on the market, here is a selection of models that are suited both to the application and the adopted tonearms:
- Ortofon OM30 (33-45 and 78 RPM)
- Audio-technica AT440ML (33-45 RPM)
- Stanton Series 500 (Custom 78 RPM Styli)
- Shure V15VxMR (33-45 RPM)
Microcontroller

To relieve the transcription station from the need to be aware of and to control all the details of the turntable, a microcontroller installed into the turntable chassis has been used. In this way the transcription station can issue to the turntable high level commands and poll the status of the device via a standard serial interface, according to the protocol described in the following sections. The commands are filtered and interpreted by the microcontroller that is the sole responsible for the proper functioning of the turntable, that is, the coordination between platter rotation and arms position.

After a market survey, the PIC16F87x series of microcontrollers from Microchip (http://www.microchip.com) has been selected because these chips have on board all the needed peripherals for our application and the presence of an on-chip programmable flash EEPROM make the updating of the firmware fast and handy. Evaluation boards can be purchased from various vendors at very low cost that can be used as a base for the turntable control with the addition of very few glue logic. In particular a PIC16F877 microchip has been used, and the firmware has been developed using the ICD-87XP emulator from Advanced Transdata Corporation (http://www.adv-transdata.com). The relative evaluation board ICD-Demo has then been used for hosting the final implementation.

The following table, taken from the PIC16F87x data sheet, gives the main features of the device.

Table 1. PIC16F87x microcontroller features.

<table>
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<th>Microcontroller Core Features:</th>
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<tr>
<td>• High performance RISC CPU</td>
</tr>
<tr>
<td>• Only 35 single word instructions to learn</td>
</tr>
<tr>
<td>• All single cycle instructions except for program branches which are two cycle</td>
</tr>
<tr>
<td>• Operating speed: DC - 20 MHz clock input DC - 200 ns instruction cycle</td>
</tr>
<tr>
<td>• Up to 8K x 14 words of FLASH Program Memory. Up to 368 x 8 bytes of Data Memory (RAM)</td>
</tr>
<tr>
<td>• Pinout compatible to the PIC16C73B/74B/76/77</td>
</tr>
<tr>
<td>• Interrupt capability (up to 14 sources)</td>
</tr>
<tr>
<td>• Eight level deep hardware stack</td>
</tr>
<tr>
<td>• Direct, indirect and relative addressing modes</td>
</tr>
<tr>
<td>• Power-on Reset (POR)</td>
</tr>
<tr>
<td>• Power-up Timer (PWRT) and Oscillator Start-up Timer (OST)</td>
</tr>
<tr>
<td>• Watchdog Timer (WDT) with its own on-chip RC oscillator for reliable operation</td>
</tr>
<tr>
<td>• Programmable code protection</td>
</tr>
<tr>
<td>• Power saving SLEEP mode</td>
</tr>
<tr>
<td>• Selectable oscillator options</td>
</tr>
<tr>
<td>• Low power, high speed CMOS FLASH/EEPROM technology</td>
</tr>
<tr>
<td>• Fully static design</td>
</tr>
<tr>
<td>• In-Circuit Serial Programming (ICSP) via two pins</td>
</tr>
<tr>
<td>• Single 5V In-Circuit Serial Programming capability</td>
</tr>
<tr>
<td>• In-Circuit Debugging via two pins</td>
</tr>
<tr>
<td>• Processor read/write access to program memory</td>
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<tr>
<td>• Wide operating voltage range: 2.0V to 5.5V</td>
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<tr>
<td>• High Sink/Source Current: 25 mA</td>
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<tr>
<td>• Commercial, Industrial and Extended temperature ranges</td>
</tr>
<tr>
<td>• Low-power consumption: &lt; 0.6 mA typical @ 3V, 4 MHz - 20 µA typical @ 3V, 32 kHz &lt; 1 µA</td>
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<tr>
<td>• Typical standby current</td>
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<tr>
<th>Peripheral Features:</th>
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<tbody>
<tr>
<td>• Timer0: 8-bit timer/counter with 8-bit prescaler</td>
</tr>
<tr>
<td>• Timer1: 16-bit timer/counter with prescaler, can be incremented during SLEEP via external</td>
</tr>
<tr>
<td>crystal/clock</td>
</tr>
<tr>
<td>• Timer2: 8-bit timer/counter with 8-bit period register, prescaler and postscaler</td>
</tr>
<tr>
<td>• Two Capture, Compare, PWM modules - Capture is 16-bit, max. resolution is 12.5 ns -</td>
</tr>
</tbody>
</table>
Parking Area Sensors

The detection of end of play events, that is when the arm reaches its parking position, will be implemented using optical barriers, in order to avoid mechanical contacts that could be cause of problems due to friction and wear out.

Honeywell HOA2001 devices have been selected due to the small size and the intrinsic protection from external light derived from the use of infrared emitting diode and detector.

More information can be obtained from the following URL:

Arm Lift Motors

Arm lift automation is generally not available on high end today turntables, nor ready to use retro-fits can be found on the market. The only viable way, therefore, is to design a custom arm lift using commercial motors. Our market search has identified no motor expressly designed for this or similar applications. Then, a step motor designed for industrial automation has been selected, whose characteristics and size are compatible with the task required. Namely, we have employed a Sonceboz 7214 linear actuator (http://www.valpower.it/e_7214.htm), developed for the minimum regulation in a vehicle engine. This device, being employed in consumer applications, is available in stock in quantities and offers high reliability and long lifecycle. A prototype board with all the driving logic is also available.

3.5. Computer interface

In the absence of a standard procedure, a custom protocol has been defined to interface the automated turntable to the transcription control station. The main guidelines followed are that of privileging the simplicity of implementation and the robustness of the communication over more evoluted solutions that could minimise an already low overhead at the price of higher complexity and that could introduce critical debugging conditions.

Physical layer

The communication between the computer and the turntables is done via the standard RS232 interface.

Only TX and RX pins need to be connected, as no hardware flow control signal is used by the protocol.

The RS232 settings are: 8 bit data, 1 bit start, 1 bit stop, no parity, 9600 baud.

Protocol

The protocol is of type master-slave where the control computer acts as a master and the turntables are slaves. Each transaction is formed by a request-replay pair.
The communication is always initiated by the computer by sending a byte containing one of the valid commands listed below. The replay is always constituted by a single byte. The replay will be issued "as soon as possible", typically within few ms, while the actual execution of the operations requested could take more time. It is responsibility of the master to enquire the device about the completion of a command by polling the status byte flags.

**Command format**

A command is constituted by a single byte issued by the master with the following format:

- start0 Hex 1 request to start the motor and lower arm 0
- stop0 Hex 2 request to lift arm 0 and stop the motor
- start1 Hex 3 request to start the motor and lower arm 1
- stop1 Hex 4 request to lift arm 1 and stop the motor
- status Hex 5 device status request
- speedl Hex 6 turntable speed low byte request
- speedh Hex 7 turntable speed high byte request
- all other codes are reserved

**Reply format**

A master command must be followed by a 1 byte reply of the called device. The reply is one of the following:

- ACK Issued to acknowledge a start or stop command
- NACK Issue to reject a non valid command or a command issued to a non installed arm
- STATUS Issued in response to a status request command
- SPEEDL Issued in response to a speedl request command
- SPEEDH Issued in response to a speedh request command

The syntax is as follows:

- ACK Hex 0
- NACK Hex 1
- STATUS

<table>
<thead>
<tr>
<th>MSB</th>
<th>M</th>
<th>L0</th>
<th>E0</th>
<th>L1</th>
<th>E1</th>
</tr>
</thead>
<tbody>
<tr>
<td>res 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
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M: 1 bit signalling if the motor is in motion (1) or stopped (0)
L0: 1 bit signalling if arm 0 is lifted (0) or on the plate (1)
E0: 1 bit signalling if arm 0 has reached the parking area (1) or not (0)
L1: 1 bit signalling if arm 1 is lifted (0) or on the plate (1)
E1: 1 bit signalling if arm 1 has reached the parking area (1) or not (0)
The remaining bits are reserved and must be set to 0

**SPEED**
The turntable speed is expressed on 2 bytes. The computer must concatenate the received 2 bytes SPEEDL and SPEEDH so that a 16 bit int is formed (SPEEDH is the high byte, SPEEDL the low byte). The resulting short int gives the platter speed according to the following formula:

\[
\text{speed (RPM)} = \frac{\text{FC}}{1.5 \times \text{SCALE} \times \text{reply}}
\]

where FC=5000000 and SCALE=2

If both the arms are used, the actual action performed by the device to a start/stop request depends on the status of both the arms. That is, if a stop is called for one arm while the other is still playing, the arm is lifted but the motor is not stopped until a stop is called also for the other arm. The device reply will be ACK. The situation will be flagged in the STATUS byte. Conversely, the motor is started at the first start request.

### 3.6. Mechanical design

**Chassis**

The original chassis of the Technics SL-1210 turntable do not fit the requirements of this project with several respects: its rigidity is not sufficient to damp external vibrations and there is no space to house two tonearms. To avoid the complexity of redesigning the whole chassis, that requires precise housing for the platter, the electronics and the motor, all integrated in a direct drive implementation, we have opted for maintaining the original deck, made of steel, and for substituting the plastic chassis bottom with a custom frame.

The frame has been realised from a single aluminium block with an automatic milling machine. In this way, thanks to the amorphous nature of aluminium and the absence of joints, we can have a very sturdy and rigid frame. The table deck is then bolted to the frame. A layer of putty can be interposed to damp residual vibrations.

The isolation of the turntable from the environment is obtained by putting the frame on rubber aseismic feet. These feet also provide regulation for the levelling of the deck.

As we want to be able to play oversized records (up to 16" are known to have been produced), the tonearms must be installed in such a way to provide a sufficient clear area around the platter. We have therefore chosen to implement the arms housings on separate elements suspended on the sides of the aluminium frame. In this way, they can be kept as options and installed only if needed, while for use with the standard 33/45 RPM records a different housing has been designed that replaces the original Technics arm on the deck.

The details of the implementation can be derived from Figure 2 below.
Arm housing

As discussed in the previous paragraph, two housings need to be provided, one for the internal arm and one for the external ones. They have been both realised in milled aluminium. In the design, special attention must be drawn to the arm position tolerances, especially concerning the arm base sideway level, that, in order to fit the prescribed alignment between the arm and the platter, resulted to be lower than the deck plane. In any case the two planes must be maintained parallel. The external arm housing is made of two parts, a frame, that must be bolted to the main turntable frame, and a top plate, screwed to the frame, that houses the arm and the lift. Again, putty should be laid between the contact surfaces. The details are given in the photos of Figure 3 and Figure 3.
Arm lift

The arm lift is based on the Sonceboz 7214 linear actuator that is provided of an antirotational device that avoids the rotation of the shaft. The motor flange is bolted under the arm housing plate, drilled so that the shaft is presented right under the arm. A rod, screwed directly on the motor shaft, lifts and lowers the arm, as shown in Figure 5. As the shaft, while moving along its axis, tends to vibrate freely and could shift the arm from its vertical position, a guide has been added to the rod, that forbids any horizontal move. The provided shaft travel, 18 mm, is excessive for the application. As the motor can exert a considerable force (35 N), to avoid possible damage to the arm or the motor in case of wrong operation, two position sensors have been added to the lower end of the shaft, so that the effective travel can be trimmed according to the arm position regulation. The sensors have been implemented using the same type of optical barriers as the position sensor. Some hardware circuitry has also been added to electrically inhibit any shaft motion outside the defined area. When the shaft reaches its top position, a reed glued on it breaks one of the barriers, causing an immediate stop of the motor; in the same way, when the shaft reaches its lower position, the breaking of the other barrier stops the motor. The travel can be regulated by modifying the reed shape or sliding it along the shaft (see Figure 6).
Position sensor

The position sensor is responsible for detecting the end of record playback. It has been implemented with an infrared switch triggered by a reed glued to the rear of the arm. The sensor is fixed on the arm pillar via a collar. Rotating the collar, it is possible to trim the detection position (see Figure 7).

Control hardware

The control hardware includes the microcontroller, the interfacing logic and the arm lift motor drivers. Only some interfacing logic has been developed as both the microcontroller basic deployment (RS232 interface, quartz oscillator, reset circuitry) and the motor drivers have been found on the market. The microcontroller must control the platter motor (start/stop) and the arm lifts (up/down). To report the turntable status to the transcription station it must also be able to read the output of all the sensors and to measure the rotation speed of the platter. Furthermore, as the start/stop signal accepted by the Technics motor control logic is of impulsive nature, a feedback signal must be derived to inform the microcontroller on the actual status of the motor. Examining the SL-1210 schematics, the only reliable signal found, avoiding to interfere with the normal motor operation, is a signal that goes high when the
platter brakes are activated right after a stop command is issued. This signal has been interfaced to an interrupt pin of the micro, so that its corresponding event is captured regardless of the micro activity. The platter rotation speed can be measured by connecting to the Capture module, built in the microcontroller, a signal generated by an inductor triggered by a set of magnets positioned under the platter body. The Capture module is a peripheral able to continuously measure the time elapsed between successive up fronts of a signal. The measurement has a direct relation with the rotation period of the platter, as defined in the Computer Interface section (see for details Figure 8, Figure 9 and Figure 10).

**Figure 8. Turntable control logic schematics.**

**Figure 9. Arm lift motor position sensors logic.**
Figure 10. Microcontroller board.

Figure 11. The control hardware. This box is screwed under the frame bottom.

Microcontroller firmware

The flow of the microcontroller firmware is described in the block diagrams below. At reset, after the initialisation of local variables and peripherals, the program loops in an idle cycle.
waiting for commands from the controlling station (Figure 12). Upon reception of a byte on the serial interface, the value is analysed to see if it is a valid command, if not it is rejected and a NACK reply is sent back on the serial interface, otherwise the command is executed. If the command is a status request, a status byte is assembled by reading the value of arm lift and position sensors and immediately sent back on the interface; analogously, if the command is a request of platter rotation speed, the Capture Register is read and the low or high byte copied on the interface according to the request: it is up to the controlling station to reassemble the two bytes and convert the value in rounds per minute (RPM). If the command is a start or a stop, then a ACK reply is immediately sent back and the command execution is then started (Figure 13).

The command execution consists of driving up or down the corresponding arm and of starting or stopping the platter motor, taking also into account the status of the other arm. Completed the command execution, the program returns to its idle loop waiting for a new command to execute (Figure 14).
Figure 14. Start and Stop commands execution.

78 RPM speed implementation

The Technics SL-1210 speed is regulated by a AN6680 chip, according to a reference frequency generated by a crystal oscillator. Modifying this frequency, it is possible to implement any wanted rotation speed. The modifications that need to be applied to the SL-1210 control are shown in Figure 8. The switch selects the reference frequency source: on board for 33/45 RPM or coming from the added oscillator for 78 RPM. When the latter is selected, the two switches on the deck for selecting 33 or 45 RPM are disabled. This condition is flagged by switching both the corresponding leds on.

Figure 15. Hardware modification for 78 RPM implementation.

3.8. Turntable Set up and Tuning

The turntable set up depends on the type of records that must be processed by the transcription chain.

The following configurations are possible:

- Single SME 309 tonearm with either or for 78 RPM records. Records of size greater than 12” will not be playable.
- Single SME 312 tonearm with cartridge and stylus either for 33/45 RPM records or for 78 RPM records. Records of up to 16" can be played.
- Two SME 312 tonearms, one with cartridge and stylus for 33/45 RPM records and one for 78 RPM records. Records of up to 16" can be played.
- Two SME 312 tonearms with different styli for 78 RPM records. Records of up to 16" can be played.

![Figure 16. The assembled turntable.](image)

The tuning of the unit requires proper trimming of the tonearm(s), following the instructions given in the SME 300 Series manual, and careful levelling of the deck that must be laying perfectly horizontal to avoid the generation of any unwanted skating forces on the pick up. The levelling can be done, with the help of a spirit-level laid on the platter, by slightly turning the turntable feet. The trimming of the tonearms is more time consuming and must be done by an expert technician with the help of the arm manual. Finally, the arm lift must be positioned in such a way that it lifts the arm at least 5 mm over the record when in rest position and that it doesn't interfere with it when in playing position. The regulation can be done either by sliding appropriately the sensors reeds along the shaft of the motors, or by easing the screw that holds the rod of the lift on the motor shaft and moving it up or down as needed.

### 3.9. Further Design Optimisation Ideas

While planning the building of small series of the turntable, it can be considered the opportunity of looking for further project optimisations, both in the direction of improving the turntable characteristics and reducing the implementation costs. Here are some preliminary ideas:

- Integration of the turntable deck in the frame bottom, that is deriving the driving motor, electronics and platter housing directly in the aluminium block used for the frame base. This would further increase the rigidity of the whole and the rejection to microvibrations.
- Selection of smaller arm lift motors. The motor used are actually conceived for higher workloads and are over dimensioned for this use. Smaller motors would reduce costs and vibrations.
- Integration of the control hardware. For the prototype implementation purposes, evaluation boards provided by manufacturers of developing tools have been used. The design of a custom board would reduce costs and size of the electronics.
4. A/D conversion technology selection

4.1. Key Link description

All the modern implementations of audio Analogue to Digital (A/D) converters use devices based on the Sigma-Delta modulation technique that solves several problems generally found on traditional parallel converters. Sigma-Delta converters are in fact intrinsically linear over all the usable dynamic range and several devices on the market show that with this technology true 20 bit resolution can be obtained, giving a Total Harmonic Distortion + Noise (THD+N) figure of -120 dB. Recently, a new approach to A/D conversion has been proposed, based on the use of a parallel of up to 4 Sigma-Delta converters, appropriately scaled to cover distinct dynamic ranges. The output of the single converters is then combined to obtain the digital representation of the analogue signal. The philosophy of this approach is that of extending the dynamic range of the converter up to 150 dB, while maintaining the THD+N constant at about -100 dB in a range of 50 dB of the input signal. Having diverging measurement results, namely higher dynamic range and lower THD+N, it is not trivial to instrumentally determine if this approach brings any benefit to the quality of the conversion compared to that employing a single Sigma-Delta converter, but further investigations, including listening tests are needed to understand how the perceptibility of the quantisation noise/distortion produced by this equipment compares to that of state of the art single converter equipment.

The work of this key link has been organized into three phases:

- Selection of state of the art equipment to test
- Objective measurements
- Subjective evaluations

In drawing the conclusions of this analysis special attention will be given to distinguish, when possible, between differences due to the specific implementation of the tested equipment and differences peculiar to the different conversion approach, as only the latter are relevant for the key link.

4.2. Equipment selection

The market offer of A/D Sigma Delta conversion units is very ample, and several manufacturers produce state of the art equipment. We decided to include in the test the Apogee PSX-100, because it is a popular apparatus, well known in the broadcast environment not only for its conversion quality but also for its flexibility. It offers, in fact, 2 channels at 24 bits sampled at up to 96 kHz, several digital output interface options, quality monitor D/A conversion and a selection of dithering and synching options. For the details, please refer to table 1.

The quad Sigma Delta configuration is patented and offered only by Stagetec, a German company well known for digital routers and mixers. Recently, they decided to produce a stand alone conversion unit, named TrueMatch RMC, derived from the A/D developed to equip their digital mixers. Beside the standard line level inputs, this unit can be equipped with microphone inputs, thus avoiding the need for external preamplifiers. It can be configured with 8, 16 or 24 inputs at 28 bits. It must be noted, however, that the lowest 4 bits of each sample can be obtained only when interfacing the unit with another Stagetec product via a custom interface, as the standard audio digital interfaces handle only up to 24 bits. Therefore, all the tests that we have performed are done using 24 bit output. Refer to table 2 for the details of the TrueMatch characteristics.
Apogee PSX-100 features

- Two channels 24-bit A/D and D/A conversion with 117 dB dynamic range
- Sampling Frequency at 44.1, 48, 88.2 and 96 kHz
- Built in interfaces: AES, ADAT, TDIF, S/PDIF (coax and optical)
- Apogee Bit-Splitting™ allows 16-bit recorders to be used to store 24-bit and even 24/96 kHz signals
- Operating modes: Confidence Monitor, Digital Copy, Analog Monitor
- Apogee Soft Limit®
- Apogee's UV22® dithers 24-bit signals to 20 or 16 bits
- 2-channel LED bar metering
- User-definable over detection (1-4 digital FS)
- AES/EBU distribution amplifier capability
- Balanced or unbalanced analog I/O
- Gold-plated XLR jacks for analog and AES/EBU I/O
- RCA jacks for S/PDIF in and out
- Two proprietary Apogee low-jitter master clocks
- Optional video sync module

Stagetec TrueMatch RMC features

- 8/12/16/24 microphone inputs, 28-bit resolution
- 153 dB (RMS) converter dynamics
- balanced transformer-insulated XLR inputs
- phantom power supplied
- subsonic filter with adjustable cutoff frequency
- phase inversion
- adjustable digital gain
- output format: AES/EBU, S/PDIF
- noise shaping available, re-quantization to 20 or 16 bits with dithering
- wordclock input for external synchronization (BNC connector)
- wordclock output (BNC connector), suitable as master clock
- balanced transformer-insulated outputs
- serial computer interface (RS232; 25-pole sub-D connector) and USB
- connectors (depending on version): XLR male, BNC, D-Sub, Toslink/DNP, Cinch/RCA

4.3. Objective measurements

To verify the technical specifications provided by the manufacturers of the two equipment and to be able to compare them on an objective basis, an extensive set of measurements have been performed. The measurements have been done using the Audio Precision System 2, a state of the art audio measurement equipment, widely used by audio experts. Both the AD converters have been connected to the System 2 using their AES/EBU digital output. As the AES/EBU interface is capable of carrying up to 24 bits per audio sample, the 28 bit capability of the TrueMatch has not been assessed. On the other hand, as already stated, 28 bit connection is available only by using non standard interfaces and is therefore hardly usable in a mixed vendor environment.

The complete set of measurements is reproduced below with a short interpretation of the results.
FFT 1kHz
This measure consists of computing the Fast Fourier Transform (FFT) of a pure 1 kHz sine tone converted by the unit. With this measurement, by varying the amplitude of the test signal, it is possible to estimate the maximum input level accepted by the apparatus, as the signal spectrum is heavily affected by out of range signals. Furthermore, it shows the distribution of the background noise and the presence of distortion components. The graphics below show that the PSX100 can accept signals at up to 19.9 dBU, while at 20 dBU the distortion is clearly unacceptable. The TrueMatch instead can go up to 22 dBU. This values give the digital full scale level, generally indicated with 0dBFS, of the two equipment. As there is a mismatch of 2 dB between the two units, all the measures will be executed correcting the input levels accordingly. The noise floor is located at -140 dBFS for all the measured conditions. Unfortunately, this is due to the limit in resolution of the System 2. It is then to be expected that the real noise floor of the equipment be at a lower value.
**Frequency response**
The frequency response has been calculated at full scale and 16 dB below, to verify if the input level affects the measure. The results are extremely good for both the units, as is generally the case with today state of the art converters.

**Channel separation (crosstalk)**
The channel separation is computed by measuring the level at the output of a channel of the stereo pair while a sine test signal is presented at the input of the other. The measure has been performed at two amplitudes: 1 dB and 16 dB below full scale. In this case the Stagetec unit outperforms the Apogee, even if the values are very good in both cases.

**THD+N**
Total Harmonic Distortion + Noise (THD+N) is one of the most important and selective measures. It express the effective resolution power of the AD converter as function of the input level. Unfortunately, it cannot discriminate between noise (wide spectrum) and harmonic distortion (frequencies located a multiples of the input signal), therefore it is not possible to determine from this measure the related perceptual effect. Use FFT graphs to draw a qualitative estimation of the distribution of noise and distortion. To obtain a realistic
estimation of the perception of the distortion and noise components, a weighting mask can be applied to the signal derived from the observation of sensibility thresholds of the human ear. Generally, plotting the THD+N value function of the amplitude of the input signal, the shape of this curves is flat with some rise when the level approaches the maximum permitted. The PSX100 follows this shape, while the TrueMatch has a quite peculiar behaviour, due to its non conventional architecture: for input levels above 0 dBU its distortion is consistently 4 dB higher than that of the PSX100, but for lower input levels it improves. Keeping constant the amplitude and varying the frequency, we can still observe a flat curve for amplitudes several dB under the maximum level, while approaching full scale both the units show some irregularity and pronounced differences between the left and right channel.

**Intermodulation Distortion (IMD)**

Intermodulation distortion gives a measure of distortion products not harmonically related to the pure signal. This is important since these artifacts make music sound harsh and unpleasant. This measure can be considered complementary to THD as here the frequencies sought are those produced by the combined effect of two or more tones, that are therefore multiples of the difference of the frequency of each pair of tones. There are several methods to measure the IMD, including SMPTE, CCIF and DIM. The first two are based on the combination of two sine tones, while the latter uses a combination of a sine tone with a square one. All of them have been computed, but for brevity we report here only the SMPTE, which is slightly easier to read than the others. The results are however substantially confirmed by the other methods. SMPTE IMD uses a test signal made of a 60 Hz tone combined with a 7 kHz tone in the ratio 4:1. The analysis is done by observing the presence and amount of intermodulation terms around the 7 kHz frequency, represented by frequencies located at 7 kHz ± n*60 Hz. The FFT of the output signal has been plotted at two input levels: 1 dB and 16 dB below full scale. From the resulting graphs it can be observed that the TrueMatch presents higher distortion than the PSX100, especially at -16 dBFS. But looking at the next graph where the result of the test has been plotted sweeping the input level from 0 to -50 dBFS, the conclusions are contradictory. The two units present similar behaviours in the range between -2 and -15 dBFS but then the TrueMatch curve becomes very irregular and
significantly worse than that of the PSX100 until -25 dBFS, where the situation reverses while going towards the lower levels. Its is then very difficult to predict what could be the impact on perception of this unusual characteristic.

**Linearity**

Linearity is a measure of how much the converter steps differ from the theoretical values. With modern Sigma-Delta modulation based converters, this measure is useful to estimate the practical dynamic range of the equipment, because the design method ensures the linearity in the intermediate steps. Two curves are drawn in the graphics: the diagonal blue ones represent the converted value of the input level, while the red and green ones show the difference between the converter output and its theoretical value expressed in dB for the two channels of the stereo pair. The PSX100 has an effective dynamic range of about 120 dB, corresponding to 20 bits, similar to its distortion level shown by the THD+N figure (considering its best channel), but the TrueMatch has a dynamic range of more than 140 dB, corresponding to almost 24 bits, much higher than its THD+N value, that could not be achieved even in theory, due to the thermical noise of analog components.
This measure, combined with the THD+N, show that the TrueMatch behaviour is substantially independent from the input level of the signal, while the PSX100 presents a pedestal at about -90 dBu that limits the converter resolution towards the low levels.

4.4. Subjective tests

Objective
It is well known that objective measurements can give only partial information about the overall quality of sound. This is mainly due to the fact that objective measurements cannot account for the plethora of non linear couplings that occur when complex sounds (in the meaning of not pure sine tones) are processed by an electro-acoustic chain and by the human ear. Therefore, listening is the only means that we have to rate the quality of equipment when the objective measurements give contradictory information, namely in our case: better dynamic range and worse distortion in some part of the audio dynamic range.

The questions that we try to answer with this subjective experiment are:

   a) Is the different distortion characteristic (THD+N and IMD) of the two units a discriminator in the transcription of archive materials application?
   b) Is the extended dynamic range of the TrueMatch bringing a valuable plus to the conversion in the archive application?
   c) Is one of the two units globally better performing than the other?

Test methodology
The tests have been performed using the expert panel method, widely adopted by the broadcast community to evaluate the quality of production equipment. It consists of comparative observation of source and processed material in varying listening conditions by a panel of expert listeners. The listeners are free to talk to each other and to exchange opinions. This method is less rigorous than the classical double blind test, used by both audio and video communities to qualify coding systems, but, when the quality of the signals to be evaluated is very high, it generally produces valid results at a much lower cost.
For these tests, we gathered a panel of 5 expert listeners, 3 working in the audio group of the RAI Research Centre and the others audio technicians of the RAI Production Centre of Turin.

Test conditions
The two A/D converters have been compared in the following conditions:

1. live recording of a performance of the RAI symphonic orchestra
2. transcription of various samples of archive materials (tapes and vinyl)
3. transcription of archive materials at levels significantly lower than the nominal
Condition 1 has been included to evaluate the digitisation fidelity of the two units for high quality, high dynamic range music. It consisted of a stereo recording of a rehearsal session of the RAI orchestra in the Turin Giovanni Agnelli auditorium, performing Stravinskij's "Concert in D for violin and orchestra". The sound has been recorded simultaneously in three versions, two digital at 24 bit/sample, 48 kHz, captured by the two units under test, and an analog one recorded with a 1/4" Studer A812 on a high quality tape at 15 inch/s speed, used during the listening as a reference. The set up of the recording is shown in Figure 17. Note that, even if the TrueMatch converter can be connected directly to the microphones, a preamplifier has been used instead in order to match as close as possible the recording condition of the PSX100.

![Figure 17. Live recording set up.](image)

Condition 2 is the simulation of the normal working condition expected in our application. It is significantly different from the former case because here the dynamic range of the signal is much lower due to the intrinsic limitations of the legacy analog recording media. Several types of supports and content have been used, including classical and pop 33 RPM vinyl from various periods and magnetic tape 1/4" recordings of music, see the table below.

Condition 3 has been added to stress the equipment and verify the usability of the extended dynamic range of the TrueMatch. This condition can be meaningful in simulating mass transcription chains when some material can have been recorded on the original media at a non standard level and the realignment of the equipment at each single transcription is unpractical. Here the source consisted of the same material used for condition 2 attenuated by 30 dB before the A/D input. The digital signal has then been realigned at nominal level before playback, in order to avoid differences in perception due to the different listening level.

<table>
<thead>
<tr>
<th>Author</th>
<th>Title</th>
<th>Serial number</th>
</tr>
</thead>
<tbody>
<tr>
<td>BARRY WHITE</td>
<td>LET THE MUSIC PLAY</td>
<td>6370 2412A</td>
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<tr>
<td>DIRE STRAITS</td>
<td>LOVE OVER GOLD</td>
<td>6359 109</td>
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<tr>
<td>DEMIS ROSSOS</td>
<td>HAPPY TO BE...</td>
<td>9120 088A</td>
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<tr>
<td>FAUSTO PAPETTI</td>
<td>SAX 20a RACCOLTA</td>
<td>Ms AL 77363</td>
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<td>JAZ</td>
<td>CBS 25724</td>
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<td>THE PHANTOMS</td>
<td>FLP 704</td>
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<td>FABIO FABOR</td>
<td>PAPE SATAN</td>
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<td>BONEY M.</td>
<td>NIGHTFLIGHT TO...</td>
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<tr>
<td>GAZERO</td>
<td>GAZERO</td>
<td>BR 86050</td>
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* Tape speed 15 inch/s
The expert panel sessions were carried out in the RAI Research Centre listening room using the set ups shown in Figure 18 and Figure 19. The first was used for condition 1 and 3, while the other for condition 2. In all the set ups the listeners could freely switch between the various sources, that were playing synchronously, and between loudspeakers (Genelec S30C amplified studio monitors) and headphones (Stax Labda Pro with diffuse field equaliser). The same D/A converter, embedded in a second the PSX100, was used to reconvert into analog format the digital sources. The original analog source was also available (except for Condition 1) as a reference.

![Figure 18. Comparison between analog source and Stagetec or Apogee digital conversion.](image)

![Figure 19. Comparison of analog vs. digital (Apogee and Stagetec) prerecorded material.](image)
Listening considerations
All the test configurations proved to be very difficult for the listeners, given the high quality of both the units under test, and the perceived differences rather small. A limitation to the discriminating power of the listeners could have been the D/A converter resolution, whose characteristics are barely able to match those of the A/Ds under test. This problem, however, cannot be easily overcome because the market is giving much more attention to the performance of analog to digital conversion, as this affects the overall quality of the sound product, than to the quality of digital to analog conversion, relegated today to signal monitoring applications. This limitation was somewhat overcome in Test condition 3 by digitising signals at low levels, thus reducing artificially the usable dynamic range of the A/D converters, and reproducing them at full level.

Condition 1
This test was considered the most difficult, because during the comparative listening the original signal source (the orchestra) was obviously not available. An analog recording done with a Studer A812 unit was used instead. The panel was warned, however, that the dynamic range of the Studer was not able to match that of the digital units and therefore that some caution had to be used during the comparisons.

The final panel impressions are:

- The perceivable differences between the two digital versions of the recording are marginal, while the analog recording lacks of details in the low levels.
- The recording done with the TrueMatch sounds more brilliant than that done with the PSX-100. A comparison with the A812 recording however, suggests that the PSX-100 sound is more faithful to the original.
- Instrument attacks are more defined in the TrueMatch recording. This improves the overall stereophonic image and sound definition.

Condition 2
Several records were played on the turntable, while the panel could switch between the various sources. This time the original source was available to the panel and constituted a valid reference. Again, the sound of the TrueMatch processed signal was crisper than that processed with the PSX-100, which again resulted more neutral. Also this time the differences were considered rather marginal.

Condition 3
A subset of the records used in Condition 2 was converted to digital with the two units at low level and recorded on a digital workstation. After realigning the levels at nominal level, the two versions have been compared in the same set up as Condition 2.
This test showed more substantial differences between the two converters. The TrueMatch showed higher sound definition and clearness in the sound attacks, as it was expected from the objective measurements results.

4.5. Conclusions
A set of subjective tests was performed to verify and interpret the results of the objective measurements. Here are the inferred answers to the three questions that have been formulated to define the goal of the assessment.

- Question a): Listening considerations of Conditions 1 and 2 show that the signal digitised with the PSX-100 is slightly more faithful to the original than that digitised with the TrueMatch. This probably reflects the different THD+N and IMD characteristics measured. The perceived differences are however of modest intensity.
Question b): Condition 3 demonstrates that the wider dynamic range of the TrueMatch over the PSX-100 results in better audio quality at low levels. Given the dynamic range expected from legacy analog media, this feature is of little use for transcriptions performed at nominal level, while can become very useful in case of misaligned signals.

Question c): The two units can be considered equivalent for the transcription activity, provided that the source material be digitised at nominal level. If a wide variation in the input levels (in the order of several dB) is expected, and for mass transcription optimisation manual realignment prior to the digitisation is not acceptable, then TrueMatch offers significantly better performance than the PSX-100.

The above conclusions are not only valid for the specific units under test but they can be extended to the underlying technology, because the main perceived behaviour differences are a direct consequence of the architecture design of the converters.