Running Optimum Power Control:
Data Integrity in CD-Recording

-OSTA-
Optical Storage
Technology Association

Revision 1.0
7 Jan 98

Editor's Notes

When faith is all they have to go on when entrusting important data to optical storage and archival systems, users are not well served. Is the information being recorded correctly? Can it be read? Will it last?

By shining some light into the elements of the special writing technique known as Running Optimum Power Control (Running OPC), I hope to establish increased faith in CD-Recordable (CD-R) and well founded confidence that recordings will live up to the legitimate expectations of the user.

If you have any suggestions that might improve the usefulness or accuracy of this white paper, please feel free to contact me by telephone: (519) 474-3466, fax: (519) 474-3467 or email: hugh_bennett@compuserve.com.

Sincerely,

Hugh Bennett, Forget Me Not Information Systems Inc.
Editor, OSTA Running Optimum Power Control white paper

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Introduction

Since its arrival on the market, individuals, companies and public institutions have come to rely on the powerful capabilities of CD-Recordable (CD-R) as a trusted and valued partner. Unique in the computer and music worlds CD-R discs, once written, by their nature have high data integrity, last a long time and can be read by over 180 million CD-ROM drives and 750 million audio and other compact disc players currently in use as well as all new DVD-ROM drives and some DVD Video players. As a result, CD-R is used with confidence for data storage, audio recording, archiving, prototyping, software distribution and countless other applications.

An important reason confidence in CD-R is so well founded relates to some of the advanced techniques that are now used by CD-Recording hardware to ensure discs are correctly written. One of the most important of these is called Running Optimum Power Control or Running OPC.

Background

In general terms, CD-R discs are made up of an optical stack consisting of a polycarbonate substrate, a sensitive dye layer, a gold or silver alloy reflector and a protective lacquer overcoat. Some media manufacturers also coat discs with an additional protective layer to further protect against possible damage from handling and use.

Data is written to the disc by a CD-Recorder focusing a high power laser on the dye layer and precisely heating and locally irreversibly altering it to create a spiral track of variable length marks (low reflective areas) and lands (highly reflective spaces between the marks). The resulting pattern or combination of the modulating lengths of marks and lands, from 3 to 11 clock cycles (3T to 11T), with the 1's in the digital data stream being encoded in the mark/land boundaries (transition regions), physically encodes the data. CD players or CD-ROM drives can later retrieve the data by focusing a low-powered laser beam onto the track of marks and lands and deciphering the modulated pattern of light reflected back to a photo diode detector. (see Figure 1)

Precise mark length is therefore critical if the data is to be represented accurately. For example, if a CD-ROM drive reads a disc with a number of 3T marks or lands that are written too long it might misinterpret them as 4T features. While the sophisticated error correction used by the system can handle all but the most extreme cases, there is the possibility that the drive will be unable to retrieve the correct information or reading performance may suffer if too much correction is required.

What Is "Running OPC?"

Running OPC is a special technique used in newer CD-Recorders for monitoring and maintaining the quality of the disc writing and ensuring the accuracy of all the mark and lands lengths across the disc. The term Running OPC actually describes a general process which is also known by several trade names including "Dynamic Power Control (DPC)" and "Direct Read During Write (DRDW)." There may be differences in execution which gives some of these implementations competitive advantages over others.

Initial OPC Procedure

The correct amount of laser power needed to write a CD-R disc is variable and depends on both the individual recorder, disc and sometimes even the specific location on the disc. Due to their physical makeup, the various types of dyes used in CD-R discs have different sized power windows and therefore require different amounts of laser power for proper recording. Power window refers to the range of laser energy which will properly form the correct size marks on a disc, which not only can vary between the type of dye used but is also dependent upon the speed at which the disc is being recorded. For example, a CD-R disc written at double speed might have a power window of 2 milliwatts (mw) between the range of 8 and 10 mw. If the disc is written within this range the marks formed will be of the proper size. Too much power will create oversized marks which can interfere with each other physically and practically when being read. Too little power will produce undersized marks and the reduced signal levels during playback can, in extreme instances, cause read failure.

The additional fact that the dyes have different sensitivities to laser power at different light wavelengths is also important since recorders are allowed to use lasers which operate within an approved range (775 to 795 nm) rather than at a single frequency.

In the case of the recorder, the size and optical quality of the laser spot it uses for writing varies from unit to unit as does its wavelength, which can change depending upon temperature and other environmental conditions. The emission frequency of most lasers is temperature sensitive, and thus writing performed at the extremes of the allowable operational temperature range can result in a significant spread of wavelengths. Consequently, before starting, all recorders perform an initial Optimum Power Calibration (OPC) procedure to determine the best writing laser power setting for each disc and recorder combination.

The OPC process begins with the recorder retrieving an initial Recommended Optimum Recording Power estimate value (for a writing condition of 785 nm at 25 degrees Celsius) from the Absolute Time In Pregroove (ATIP) information encoded in the Lead-In Area of the disc. Using this setting as a starting point the recorder steps through higher and lower laser power settings while writing test information in a special reserved space of the disc called the Power Calibration Area (PCA), located before the disc's Lead In Area. (see Figure 2)

In practice the OPC procedure can vary from manufacturer to manufacturer and recorder model to model but, as an example, a recorder might obtain a beginning recording value of 5.9 mw from a disc and write fifteen times (15 ATIP frames or a fifth of a second) in the PCA with power ranging from 4.1 to 7.7 mw.

After writing the test marks at the different laser powers the recorder reads them back and looks for differences (asymmetry or beta) between the lengths of marks and lands. A negative beta means that, on average, the marks are underpowered (short) and a positive beta means that they are overpowered (long). To be broadly compatible with the various available types of media, recorders traditionally use a beta of +4% (suggested in the Orange Book Part II specification), though some units now have multiple target betas and write strategies (the latest version of the Orange Book

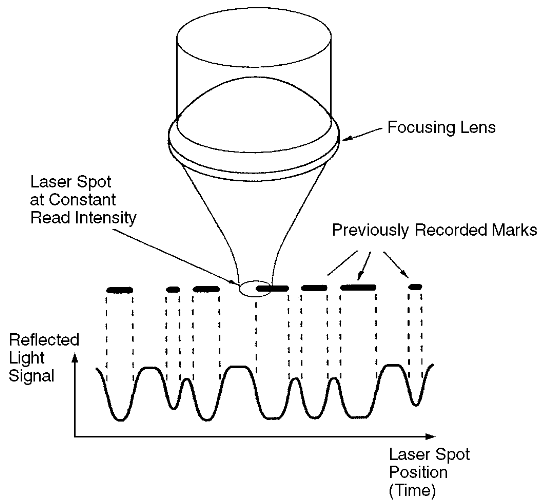

Figure 1:
The read signal created from previously recorded marks and lands on a CD-R disc.

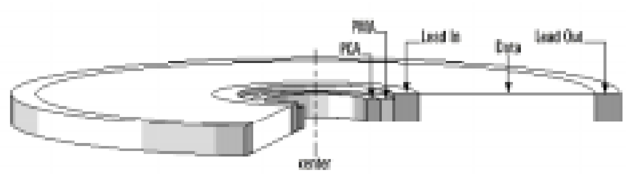

Figure 2:
Cross sectional view of a CD-R disc showing the location of the Power Calibration Area (PCA).

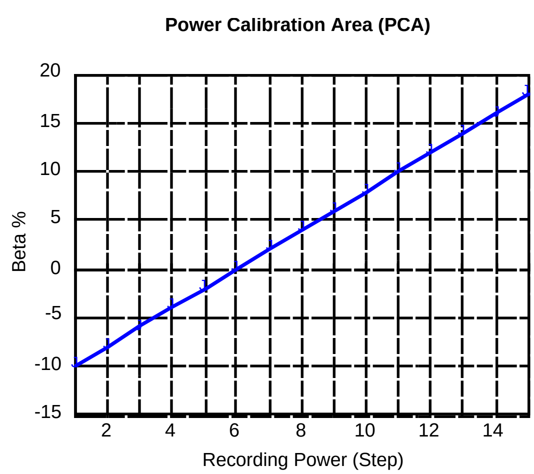

Figure 3:
Results from an Optimum Power Calibration procedure
showing a +4% beta value achieved with a recording power of 8 mw.

actually mandates the use of specific target betas and write strategies.) The recorder then determines what setting achieved the +4% beta target and establishes that as the recording power for the disc. (see Figure 3)

Some of the earliest recorders simply used the Recommended Optimum Recording Power estimate value encoded in ATIP as the established writing power, a procedure that has now been more or less abandoned since it has become clear that the optimum recording power can be a fairly sensitive function of the precise optics used in the recorder. In fact, the well publicized occurrences of over or under powered writing in the early days of CD-R were often a result of this simplistic approach.

Running OPC

A recorder with Running OPC takes this process still further. During the initial OPC procedure the recorder also monitors the reflected light coming back from the disc while the marks are forming and stores that information. After determining what power setting yields the required +4% beta the recorder retrieves the reflected signal that is associated with it, establishes a mark formation signature, and saves it in its memory. During recording the system monitors the marks as they form on the disc using the reflected light and compares these signals against the signature established during the initial OPC procedure. Laser power is then adjusted on-the-fly throughout the writing process to maintain this optimum condition. (see Figure 4)

For example, if the recorder encounters a condition that reduces the amount of laser light reaching the dye recording layer (dust, scratches, fingerprints, etc.), rather than the resulting mark being too short Running OPC will detect the change in the reflected light signal relative to the stored signature and increase the laser power to attempt to compensate. This ability to react on-the-fly is critical since the process of writing data is far less tolerant than is the process of reading data. When reading data, such features as embedded error correction schemes and strategies such as lowering the disc's rotation speed can compensate for encountered problems. By contrast, a recorder has only one brief attempt at writing data, a situation that is compounded in high speed recording. (see Figure 5)

Bandwidth

Specific situations that Running OPC can deal with depend upon the speed of response or bandwidth of the recorder. As the writing process takes place the mark formation signal is continuously being returned to the recorder, but before the hardware can interpret and use the information the signal's waveform must first be sampled. The more marks that are sampled and evaluated the higher the bandwidth and the shorter the duration of a problem for which the recorder can compensate.

For example, in a low bandwidth Running OPC scheme a recorder might only sample the formation signal returned from the longest laser pulses (11T). Since there are always fewer long marks than short marks encoded on a disc (approximately 2:1 as a consequence of the coding rules), only gradual changes from the disc's inner to outer diameter can be addressed. Compensating for more localized problems that are confined to smaller areas or particular spots on the disc is difficult for low bandwidth

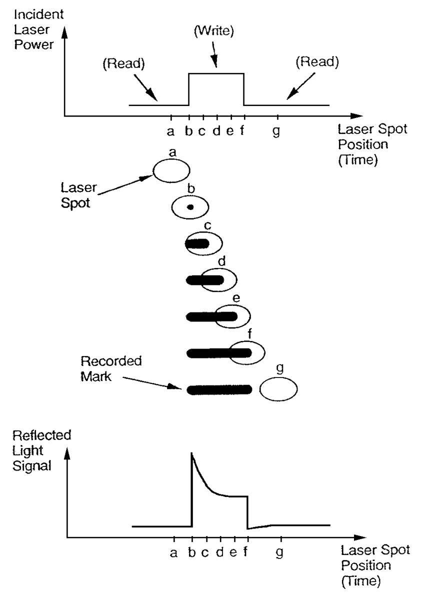

Figure 4:
A writing laser pulse and the resulting mark formation signal. The exact form of the laser pulse and shape of the signal depends upon the specific write strategy used by the recorder.

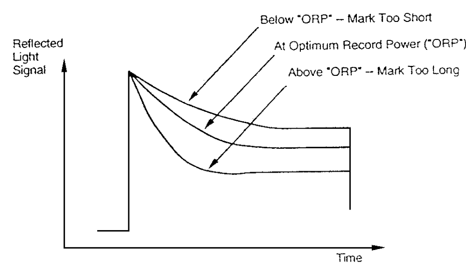

Figure 5:
A normalized mark formation signal for three recording power settings.

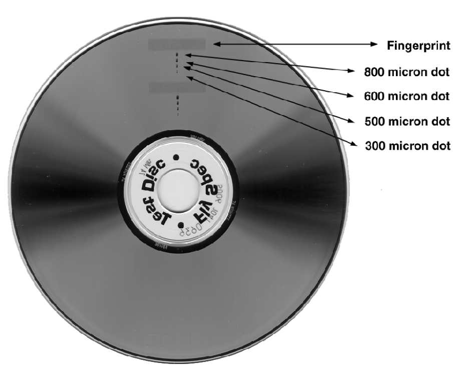

Figure 6:
An example of a "Flyspeck" disc used for evaluating the capabilities of Running OPC systems.

systems since by the time a problem is detected it may be too late to take corrective action. The types of gradual variations which reduce the amount of laser power delivered to the CD-R disc's dye recording layer that can be accommodated by low bandwidth systems include media manufacturing process issues such as variations in the thickness of the dye recording layer (conformality), substrate birefringence (optical distortion) and hardware manufacturing issues including changes in the quality of the recording spot due to wavelength shift of the writing laser, tilt, defocus and detracking as well as changes in disc performance due to wavelength shift, temperature, tilt and clamping.

On the other hand, a recorder with high bandwidth Running OPC might sample the formation signal returned from all the laser pulses (3T to 11T) and as a result has very current information to use to make adjustments for not only gradual, but also rapid variations which diminish the amount of laser power available on the disc for writing, including dust, scratches and fingerprints on the laser incident surface of the disc. The additional ability to compensate for such possible recording hazards is especially important in multisession or packet writing situations, where a disc may be handled many times over and be subjected to physical abuse between recordings.

Many recorder manufacturers evaluate and quantify the capabilities of their Running OPC systems by conducting tests using specially prepared "Flyspeck" discs which have more or less standard simulated fingerprint patterns and dust spots of various sizes printed onto them. (see Figure 6)

Absorption Control Warning

In the event that an issue can't be dealt with, some recorders generate an "Absorption Control" warning to let the user know that there may be a problem in that particular region of the disc. This can be done in several ways.

The first technique involves monitoring the amount of laser power the recorder is using to write marks on the disc and comparing it against the optimum value established before writing began. If the power exceeds a predetermined threshold for a certain amount of time, for example 20% higher than nominal, a flag goes up and the warning message is issued.

Rather than using the writing power level, the second method monitors the mark formation signal during recording and compares it against the optimum formation signature established at the outset. When the signal falls below or wanders from optimum for a predetermined amount of time, a flag is raised and the absorption control warning message is issued. Since compact discs employ various levels of error correction that can compensate for some errors in the recorded data, the precise amount of time that the signal can deviate from the optimum is based on the number of consecutive errors (burst errors) the CD player hardware can compensate for.

Data Verification

Running OPC helps detect potential data errors and provides a degree of data integrity verification. It can be used to indicate areas where possible problems have been detected and have the system go back and verify only those areas later, thereby increasing verification speed significantly. In fact this has been implement in many professional authoring systems where data integrity is a key requirement.

What Running OPC doesn't do is provide instantaneous read-back verification of the data after it is written. This is the domain of Direct Read After Write (DRAW) systems which use a second laser beam trailing the writing laser to determine if the correct data has been recorded on the disc. Because DRAW systems require extra hardware to provide and control the additional laser beam, they are expensive to commercialize and are therefore generally reserved for industrial mastering systems and not for professional or consumer CD-Recorders. Alternatively, the user obviously has the option to make a verification pass after writing as is done in Magneto-Optical (MO) and most other storage devices.

While Running OPC is very powerful it has its limits in terms of data verification. It will indicate if correct mark formation is taking place on the disc, but not if the correct data is being written. For example, if there is an issue that causes incorrect data to be transferred to the recorder, such as a SCSI termination problem, the data corruption cannot be identified by a Running OPC technique — only read back verification comparing the source data to the written disc after the fact will reveal that. Typically CD-Recorders can be set up and initially checked for data integrity and unless the configuration changes there should not be any data corruption problems, except in the unlikely event of some type of component failure.

How much integrity checking and data verification a user decides to do is really a question of acceptable risks for the application. This includes not only Running OPC and data comparison using the recorder but also the use of low-level analyzers and interchange testing on a variety of commercially available CD-ROM drives.

What About DVD?

Following its successful implementation in CD-Recorders, it is important to note that version 1.0 of the DVD-Recordable (DVD-R) specification also recommends the use of Running OPC. Apart from the welcome data integrity enhancement, Running OPC provides hardware and media manufacturers another tool for dealing with the much tighter tolerances that are, for example, a result of using high numerical aperture optical systems (0.6 NA for DVD-R vs. 0.47 NA for CD-R) for high density DVD recording.

Running OPC In Perspective

Ensuring that consumers can write high quality CD-R discs is the responsibility of both the media and recorder manufacturers. Running OPC is an important tool used to help fulfill that obligation. However, what makes Running OPC so compelling is the fact that it is in everyone's best interest.

Running OPC's ability to compensate for fluctuations encountered in both the recorder and media helps manufacturers greatly by allowing increased product tolerances and thereby reduce costs. The additional hardware and software programming needed for

Running OPC obviously costs a little more, but that increase is more than offset by the opportunity to use less expensive components, materials or processes.

The powerful ability of Running OPC to compensate for substantial degradations in recording conditions is readily apparent in Figures 7-10 where, despite large variations in parameters such as tilt and tracking and focus offsets, Running OPC maintains optimally recorded marks. (see Figures 7-10)

In addition to lower CD-R media and recorder prices, consumers most importantly benefit from a more reliable recording system with superior data integrity. Confidence comes from knowing that the recorder is not only correctly writing the disc, but optimally writing it for the best possible result. Assurance also comes from knowing that even in the event of a problem the recorder is intelligent enough to detect and advise of the situation.

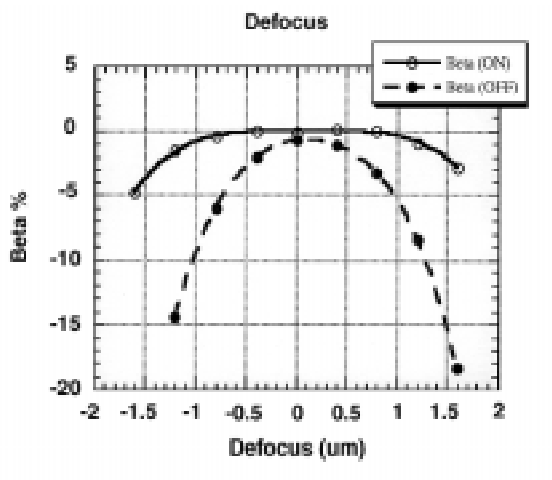

Figure 7:
Beta values from a disc written with and without Running OPC under defocus conditions.

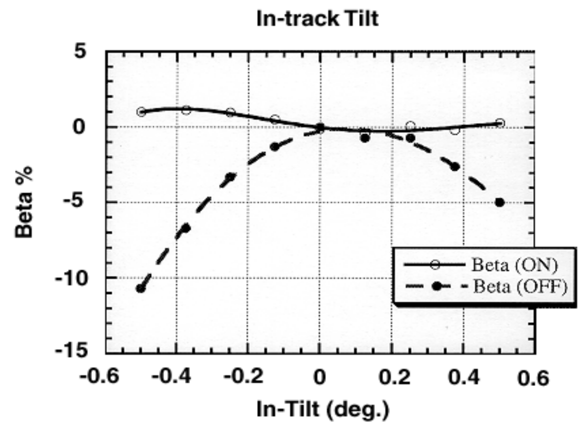

Figure 8:
Beta values from a disc written with and without Running OPC under in-track tilt conditions.

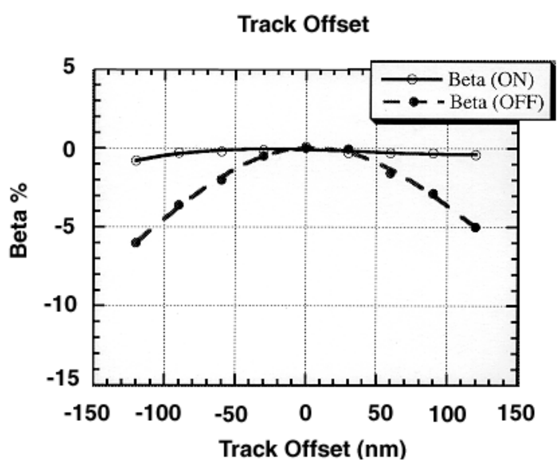

Figure 9:
Beta values from a disc written with and without Running OPC under track offset conditions.

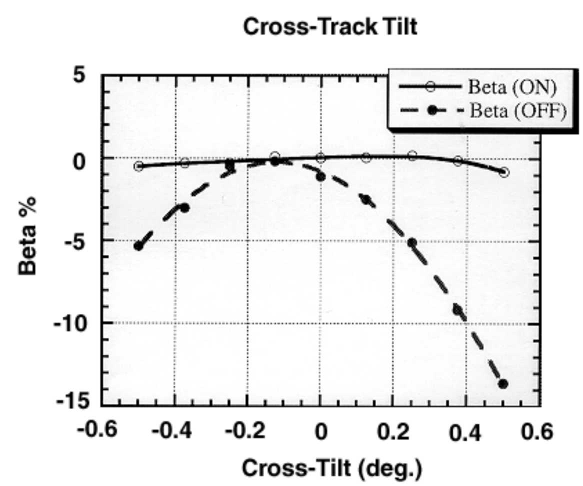

Figure 10:
Beta values from a disc written with and without Running OPC under cross-tilt conditions.

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Glossary

Absolute Time In Pregroove (ATIP)
The reflected light returned from the pregroove of a CD-R disc generates a carrier signal providing tracking, motor control and focus signals. Additional information including the Recommended Optimum Recording Power value is also encoded in a frequency modulation of the carrier signal.

Absorption Control Warning
A warning message issued by a recorder when writing power exceeds a predetermined safety threshold or if the mark formation signal returned from the disc being recorded significantly deviates from the mark formation signature.

Asymmetry
The difference between the lengths of marks and lands. Also known as Beta.

Mark formation signal
The signal created from light reflected back to the recorder's photodetector during the writing process.

Mark formation signature
The waveform of the optimum mark formation signal captured during the Optimum Power Calibration procedure.

Optimum Power Calibration (OPC)
A process by which a recorder determines the best writing laser power setting for each disc and recorder combination.

Pregroove
A slightly wobbled spiral groove molded into the substrate of a CD-R disc which provides a guide for the writing laser as well as timing and other information critical to the writing operation.

Power Calibration Area (PCA)
A special area of a CD-R disc reserved for use by a recorder in Optimum Power Calibration procedures.

Recommended Optimum Recording Power
An initial write power setting encoded in the Absolute Time In Pregroove information of a CD-R disc which acts as a starting point for the Optimum Power Calibration procedure.

Running Optimum Power Control (Running OPC)
A technique used by recorders for monitoring and maintaining the accuracy of all the mark and land lengths across a CD-R disc.

Running OPC Bandwidth
The speed at which a recorder can respond to changing writing conditions.