

Next Generation Sequencing

Bioinformatics mRNA-Seq Data Analysis

Guidelines

GenomeScans' Guidelines for mRNA Sequencing Analysis

Using our own proprietary data analysis pipelines

Dear customer,

As of the beginning of 2015 ServiceXS became a trademark of GenomeScan B.V. GenomeScan focuses exclusively on Molecular Diagnostics whereas our ServiceXS trademark is intended for your R&D projects.

GenomeScan is dedicated to help you design and perform Next Generation Sequencing (NGS) experiments that generate high quality results. This guide provides information for our data analysis services and resources and tools for further analysis of your sequencing data. NGS experiments result in vast amounts of data and therefore data analysis can be challenging. Our ability to assist in the analysis of your results can be the key factor leading to a successful project.

Our experience in the past years is that even state-of-the-art NGS software is not always able to fulfil the data analysis needs of our customers. To alleviate this problem our experienced team of bioinformaticians and molecular biologists can provide standard or custom bioinformatics solutions to get the most out of your project.

GenomeScan provides a comprehensive package of bioinformatics services for our NGS customers, which enable them to utilise all the applications that are possible with billions of bases of sequence data per run. GenomeScan can advise and assist you in every step of the data analysis. Do not hesitate to contact us if you have any questions after reading this guideline!

On behalf of the Bioinformatics team,

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Project Manager

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Changes to Previous Version (1.0)

-Layout changes



Chapter 1 Introduction

Ever since the first gene sequence was identified within a bacterium in 1972, molecular biologists have focussed on studying gene regulation and the ribonucleic acid (RNA) products that are derived from the gene sequences.

There are several classes of these RNA molecules in a cell, most of them (rRNA, tRNA, etc) are involved in producing peptides and protein structures that are used for household function. Approximately, two percent of all RNAs in a given cell are sequences called messenger RNAs (mRNAs). These mRNAs encode the actual peptide sequence of proteins, and are used as a blueprint for making proteins. In broad terms, this means that if other factors within a cell remain constant, that mRNA abundance levels determine how often a certain protein is produced, which in turn changes a cells phenotype. These changes affect the cell, tissues, and organism, for example in terms of growth, hormone production, and also when disease occurs.

Measuring mRNA transcript amounts in a cell can tell a researcher many things about the state it is in. Over the years many methods were devised to measure mRNA levels within a cell or tissue. It was soon recognised that genes are regulated within complex pathways and can function as antagonists for some genes and protagonists for others. This meant that to get a good overview of the activities within a cell, many if not all genes must be analysed at the same instance. To meet this demand, high-throughput gene expression analysis by use of microarrays was introduced. By capturing and converting mRNA from a sample to cDNA, it could be bound to a probe sequence which is hybridised on a glass microarray. By incorporating for example a fluorescent dye to the probe and the cDNA sequence, the binding of a cDNA could be measured and relative levels of cDNA (thus mRNA) could be inferred.

Since its introduction in 2009 by Wang *et al.*, mRNA sequencing is rapidly replacing gene expression microarrays in many studies and research groups. Also known as mRNA-Seq, the technique uses next-generation sequencing to create datasets containing many millions of short sequence 'reads' that describe the mRNAs found in the analysed sample.

mRNA-seq has several advantages over microarray based experiments. Since mRNA-seq does not use probes or primers, the data suffer much less from biases. The reads directly represent mRNA transcripts, not ratios between foreground and background illumination measurements on arrays. This means that mRNA-seq can register a very high dynamic range of expression levels, ranging from absolute zero to many tens of thousands of reads for one gene. This sensitivity helps with detecting rare transcripts. With microarrays, researchers of lesser known organisms have to specially design arrays for expression detection, which is not required with this method. mRNA-seq also has shown a high degree of dataset robustness across platforms and studies. mRNA-seq does require cutting edge data analysis tools and pipelines to extract the most relevant results from these large datasets.



Chapter 2 Applications

A short-read sequencer can generate many millions of short sequences that describe the mRNA transcripts that were extracted during sample preparation. To transform this raw data to relevant mRNA abundance levels information, our mRNA-Seq data analysis pipeline performs several steps which we will discuss in this chapter.

2.1 Quality filtering and trimming

The mRNA-Seq pipeline starts with quality filtering and trimming of the sequence reads. For filtering a set of standard thresholds is used which are optimised for the mRNA-Seq analysis pipeline. The main parameter defaults are:

Table 1. mRNA-Seq pipeline settings

Filter	Default	Description
Adapter trimming	On	Illumina sequencing adapters are removed
Minimal Q-score	22	All bases in the read should have at least a Q-score of 22 (corresponding to a chance of one error in 160 bases), bases with lower qualities are trimmed off
Minimal read length	36	After trimming bases reads should be at least 36 bp to be kept in the data set
Paired-end	On	For paired-end reads both reads should be kept or removed altogether
5' or 3' trim	Off	5' and 3' end of reads can be optionally trimmed for adapter sequences or other unwanted bases indicated by the customer

Presumed adapter sequences are removed from the read when the bases match a sequence in the adapter sequence set (Illumina TruSeq adapters) with two or less mismatches and an alignment quality of at least 12. To remove noise introduced by sequencing errors, reads are filtered and clipped by quality. By default, the reads are filtered using a phred score of Q22 as a minimum threshold. Bases with phred scores below this level are removed and as a consequence reads are split. If the resulting reads are shorter than the minimal read length (36 bp by default), the reads are removed altogether (both pairs in paired-end reads) when paired-end mode is used.

The filtered reads are written to FASTQ format and filtering statistics are calculated and reported. The filtered reads are used for the next stage of the pipeline.

2.2 Alignment

Considering the nature of reads based on mRNA transcripts (e.g. exon junctions, alternative splicing) a mRNA-specific tool is used. The tool uses a short-read aligner based on Burrows-Wheeler Transform to ensure maximum sensitivity for mapping reads to exons of genes. A mismatch rate of 2% (2 mismatches in a read of 100 bases) is used by default. The alignment files (BAM files sorted and indexed .bam files according to SAM specifications) containing the mapped read information are provided on the data disk in the Alignments folder.

2.3 Mapped mRNA Counting

After the reads are mapped to the reference and stored in the BAM file, a mRNA quantifying tool will count all the reads that map to an annotated protein coding gene region of the reference. The mRNA counts are the basis for the differential expression analysis.

2.4 Normalisations

Originally, gene expression microarray analysis is based on the ratios of expression differences between two groups of samples (sample versus controls or samples under different conditions). Differential expression analysis was specifically tailored to the needs of microarray based data like normalisations, removal of systematic biases and differing experimental designs. With mRNA-Seq, this analysis shifted away towards the specificities of mRNA-Seq, namely the concept of discrete counts of mRNA transcripts sequenced into short reads. Normalisations are still required but are less complex, they are mostly focussed on the inherent probabilistic nature of short read sequencing.

The main form of RNA-Seq count normalisation results in Fragments (a.k.a. Both mapped paired-end reads counted as one fragment) per Kilobase of exon Per Million fragments mapped (FPKM) values. With FPKM values the counted mRNA reads mapped to the annotated genes are normalised to the size of the exon they align to (larger exons or genes have a higher chance to have more reads in the dataset) and also normalised for the amount of reads sequenced for the sample (to compensate for dataset size differences between samples). These FPKM values are saved in a file for all samples, found in the FPKM directory in the Analysis folder of the data disk, and can be used for general filtering and selection or differential expression analysis methods that are used in microarray based experiments.

The normalisation performed for the differential expression analysis has a different basis. This method is based on the expectation that most genes are not differentially expressed. A scaling factor for a given dataset is computed as the median of the ratio, for each gene, of its read count over its geometric mean across the whole dataset. The underlying idea is that non-differentially expressed genes should have similar read counts across samples, leading to a ratio of 1. Assuming most genes are not differentially expressed, the median of this ratio for the lane provides an estimate of the correction factor that should be applied to all read counts of this dataset to fulfill the expectation.

2.5 Differential Expression Analysis

After normalisation our pipeline continues with differential expression analysis. The method was specifically developed to find differentially expressed genes between two conditions for mRNA-Seq data with small sample size and over-dispersion, uses a model based on a negative binomial distribution and local regression to estimate the relationship between the mean and variance of each gene. Furthermore, it allows scaling factors to be easily included in the statistical test.

The differential expression analysis uses these models to calculate the difference of expression of the genes between two groups or two samples. It accurately provides the base mean levels of expression of the measured genes, fold and log₂ fold change of expression between two groups/samples, the significance (*p*-value) of the difference and the multiple testing (Benjamini-Hochberg) corrected *p*-value. The significantly over- or under expressed genes are selected and ranked based their corrected *p*-value, with a cut-off of *p*=0.05.

2.6 Principal Component Analysis

In order to get an unbiased and quick overview of the variance within the samples, we perform a Principle Component analysis on the normalised FPKM values. The Principle component analysis provides useful sample clustering and can be used to identify deviant samples.

2.7 Read Statistics

Lastly, to provide the customer with relevant sequence quality control data, we generate several read statistics, including before and after read filtering statistics, alignment, and count statistics. These values help you evaluate the quality of the dataset and identify issues if there are any.



Chapter 3 Results

3.1 Normalised Gene Expression Values

The main product of the mRNA-Seq pipeline are the normalised values of gene expression, which can be filtered and used in downstream analysis performed by the customer. The expression values are normalised using FPKM normalization as described in Chapter 2. All the genes found in the reference annotation are included, even if they do not have any associated expression. Each expressed gene is listed separately per Ensembl Gene ID and the Gene Symbol associated with the Ensembl Gene ID is also included as annotation. The FPKM file and its content is described in Chapter 4.1.

3.2 Differentially Expressed Genes

To report relevant differential expression analysis between two groups or two samples a comprehensive list with the differentially expressed genes and their associated statistics is provided. If a gene is found to be differential expressed with a corrected p -value of 0.05, it will be included in the list, and all the differentially expressed genes will be ranked according to their p -value. Each expressed gene is listed separately per Ensembl Gene ID and the Gene Symbol associated with the Ensembl Gene ID is also included as annotation. The list with differentially expressed genes is described in Chapter 4.2.

3.3 Sample Expression Heatmap

To show an overview how the expression levels of the different samples relate to each other, a sample heatmap based on expression data is generated. The heatmap also includes a cluster branching tree to identify which samples cluster together in groups. The heatmap can be used to investigate if the sample grouping during analysis is sensible and can identify deviant samples. All image file formats are described in Chapter 4.3.

3.4 MA Plot

In microarray experiments, MA plots are generated before normalisation to inform the user of any pre-existing systematic biases that need to be corrected before any further analysis can be performed. For mRNA-Seq a MA plot is produced to identify if the gene expression differential ratios show any deviations that might affect the analysis, but also to give the customer with experiences in microarray analysis a familiar overview. The plot is supplied as a PNG image, all the image files are described in Chapter 4.3.

3.5 Sample PCA Plot

To get an unbiased and quick overview of the variance within the samples, a PCA plot is optionally generated. As the name implies, the first component shows how the variance of the FPKM normalised counts appears per sample. The plot can also be used as a way to identify issues or deviant samples. The plot is supplied as a PNG image, all the image files are described in Chapter 4.3.

3.6 Read Statistics

To determine read filtering and read mapping efficiency and to investigate possible issues during of before sequencing, the pipeline generates a file with read statistics. The read statistics file and its content are described in Chapter 4.4.

3.7 Transcript Variants (optional)

One of the advantages of mRNA-Seq is that we can thoroughly identify the sequence of a mRNA transcript and classify if it is an alternative variation. This makes it possible to determine if alternative variants are found in the sample, with more sensitivity than (custom) microarrays. The file is based on the Ensembl Transcript ID and will contain counted (non-normalised) expression values and will have Gene Symbol annotation per transcript. The transcript variants file and its content is described in Chapter 4.5.



Chapter 4 File Formats

4.1 sample_id_FPKM.tab

This tab delimited file contains the FPKM-normalised gene expression values. Each row represents a gene, with Ensembl Gene ID as main identifier. The file is generated per sample, with the sample ID in the file name followed by 'FPKM.tab'. The content of the file is explained in Table 2.

Table 2. sample_id_FPKM.tab file format

Column	Field	Description
1	tracking_id	A unique identifier describing the object (Ensembl Gene ID)
2	class_code	The class_code attribute for the object, or "-" if not a transcript, or if class_code isn't present
3	nearest_ref_id	The reference transcript to which the class code refers, if any
4	gene_id	The gene_id(s) associated with the object (if multiple Ensembl Gene ID are applicable)
5	gene_short_name	The gene_short_name (Gene Symbol) associated with the object
6	tss_id	The tss_id associated with the object, or "-" if not a transcript/primary transcript, or if tss_id isn't present
7	locus	Genomic coordinates for easy browsing to the object
8	length	The number of base pairs in the transcript, or '-' if not a transcript/primary transcript
9	coverage	Estimate for the absolute depth of read coverage across the object
10	FPKM	FPKM of the object in the sample
11	FPKM_lo	The lower bound of the 95% confidence interval on the FPKM of the object in the sample
12	FPKM_hi	The upper bound of the 95% confidence interval on the FPKM of the object in the sample
13	status	Quantification status for the object in the sample. Can be one of OK (deconvolution successful), LOWDATA (too complex or shallowly sequenced), HIDATA (too many fragments in locus), or FAIL, when an ill-conditioned covariance matrix or other numerical exception prevents deconvolution.

4.2 Sequence files

This tab-delimited file contains the differential gene expression values and statistics. Each row represents a gene, with Ensembl Gene ID as main identifier. The file is generated per analysis, with the name of the analysis in the filename followed by 'Sig_Exp.tab'. The content of the file is explained in Table 3.

Table 3. analysis_Sig_Exp.tab file format

Column	Field	Description
1	GeneID	Ensembl Gene ID for which the calculation is made
2	Mean coverage	Mean expression level (at the base scale) as a joint estimate from both groups
3	BaseMeanA (Sample ID's of group)	Estimated expression level for group 1
4	BaseMeanB (Sample ID's of group)	Estimated expression level for group 2
5	BaseMeanB / baseMeanA	The level of the fold change between the groups
6	2log (baseMeanB / BaseMeanA)	The logarithm (to basis 2) of the fold change between the groups
7	P-value of log2FoldChange	<i>P</i> -value for the statistical significance of the fold change
8	adjusted p-value	<i>P</i> -value corrected for multiple testing for the fold change, to counterbalance the false discovery rate
9	rank	Rank based on the corrected <i>p</i> -value

4.3 Image Files

This section describes the various images that are generated during the pipeline analysis. All images are also explained and interpreted in the Data Analysis Report.

Analysis_heatmap_plot.png

The following image (Fig. 1) is an example of a sample expression heatmap. The file is generated per analysis, with the name of the analysis in the filename followed by 'heatmap_plot.png'. The gradient colour represents the relative variation of expression between the samples, as defined by the legend. The branching tree shows which samples group together, without being influenced by the predefined grouping.

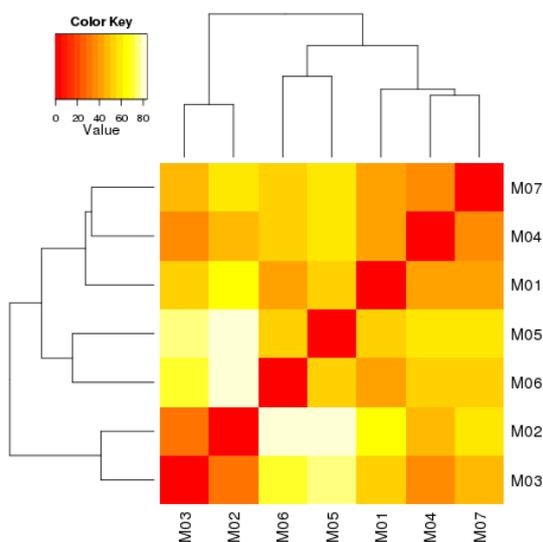


Fig. 1. Heatmap plot

Analysis_res_ma_plot.png

The following image (Fig. 2) is an example of a MA plot. The file is generated per analysis, with the name of the analysis in the file name followed by 'res_ma_plot.png'. The log₂ fold change levels are plotted against the base mean expression level to show any structural or systematic deviations and to show the differentially expressed genes, shown by the red dots. The mass of the measurements should centre around zero, because most genes do not have a deviant expression.

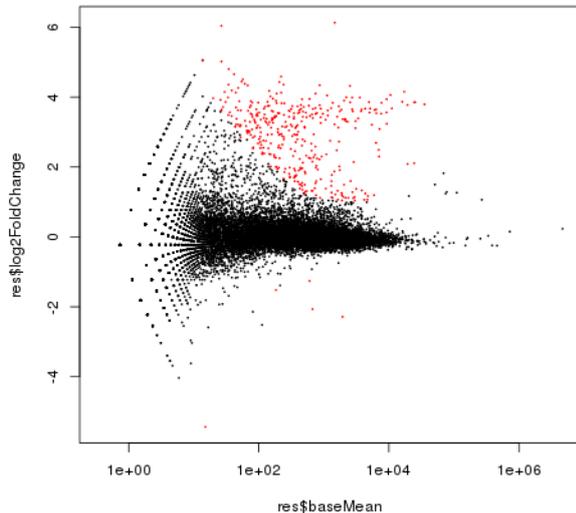


Fig. 2. MA Plot

Analysis_pca.png

The following image (Fig. 3) is an example of a Principle Component Analysis plot. The file is generated per analysis using FKPM values, with the name of the analysis in the filename followed by 'pca.png'. The PCA plot shows the relative variation based on the first two components (component 1 on x axis, component 2 on y axis). The first component (principle component) always has the highest differential power. If samples show clustering on the x axis that should be an indication that they resemble each other.

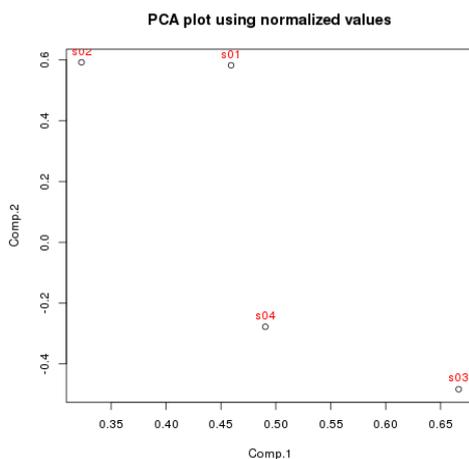


Fig. 3. PCA plot using normalised values

4.4 read_statistics.txt

This tab delimited file contains the numbers of reads and counts for the raw data and intermediate datasets. The file is generated per project, the filename is always the same. This file can be used to view the process from filtered FASTQ reads to counted mRNAs. If a loss of data occurs during analysis, this file helps pinpoint where. The content of the file is explained in Table 4.

Table 4. Read statistics

Column	Field	Description
1	Sample_Filename	Name of the sample filtered Fastq file
2	Fastq_Read_Counts	Amount of filtered Fastq reads
3	Unique_reads_in_SAM	Amount of unique and aligned reads in SAM
4	Total_Counts	Total amount of counts found by HTSeq count

4.5 counted_variants.tab (optional)

This tab delimited file contains the counts per Ensemble Transcript ID for each sample is reported. The file is generated per project, the filename is always the same. This file can be used to identify alternative transcript variants and their quantities, but is less suitable for expression analysis. The content of the file is explained in Table 5.

Table 5. Count file format

Column	Field	Description
1	Transcript ID	Transcript ID which is counted
2..n	Sample columns	Each sample is represented in one column of the table
Last	Annotation	Gene Symbol that is associated to the Transcript ID



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